Disrupting working memory to reduce verbal-analytical engagement in motor performance: Squeezing in a tiresome new approach to implicit motor learning!

by

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Abstract

Implicit motor learning paradigms aim to minimise verbal-analytical engagement during motor performance. Some do this by suppressing working memory activity during practice. This reduces the ability of the learner to use, manipulate and store task-related information via mental processes, such as hypothesis testing. Implicit motor learning paradigms that suppress working memory indirectly are not always effective, because individual differences, such as motivation, can override their efficiency. The aim of this thesis was to investigate whether two more direct methods, cognitive fatigue and hand contractions, are viable tools with which to suppress working memory activity during motor practice, and whether they cause reduced verbal-analytical engagement in motor performance.

Chapter 2 investigated whether a computer-based cognitive fatigue task suppressed working memory activity during a golf putting task. Behavioural measures of verbal-analytical engagement were employed to test whether the cognitive fatigue task reduced hypothesis testing during the subsequent golf putting task. Results revealed that the computer-based cognitive fatigue task promoted cognitive fatigue, but was not sufficient to cause reduced hypothesis testing compared to a non-fatigue group.

In Chapter 3, a cognitive fatigue task with greater emphasis on motor control was therefore designed. It was first established whether the task caused cognitive fatigue and if working memory functions were disrupted. Subsequently, it was established whether the cognitive fatigue task reduced hypothesis testing during performance of a novel shuffleboard task, using behavioural measures, including self-report and assessment of technique changes. Additionally, verbal-analytical engagement in motor planning was gauged, using electroencephalography (EEG) to assess alpha power over the left temporal verbal-analytical (T7) site plus connectivity between the T7 and Fz (motor planning mid-frontal) sites. The results revealed that the motor-specific cognitive fatigue manipulation caused increased, rather than decreased, verbal-analytical engagement in motor performance, compared to a no fatigue control condition.

Chapter 4 examined whether hand contraction protocols influenced cognitive processes during motor performance, by using EEG to gauge verbal-analytical engagement during motor planning (i.e., T7-Fz connectivity) following a left-hand, right-hand or no hand-contraction protocol. The findings revealed that left-hand contractions, which are thought to activate the less verbal right hemisphere and deactivate the more verbal left

hemisphere, caused reduced verbal-analytical engagement in motor planning, compared to the other protocols. Furthermore, right-hand contractions caused higher levels of verbal-analytical engagement in motor planning. Consequently, Chapter 5 investigated whether left-hand contractions promoted implicit motor learning. Participants practiced a motor task following regular bouts of left-hand contractions, right-hand contractions or no hand-contractions. Behavioral measures were used to gauge the extent to which verbal-analytical engagement was curtailed or encouraged. The results revealed no evidence that left-hand contractions promoted implicit motor learning, and both left-hand and right-hand contractions caused worse performance than no hand-contractions during a post-practice test phase.

Working memory performance was disrupted by both the cognitive fatigue and hand contraction protocols; however, predicted decrements in verbal-analytical engagement did not occur, and implicit motor learning was not promoted. The findings of this thesis reveal the complexity of the interrelationships between working memory, verbal-analytical processes and brain activity during motor learning. Future directions for research are considered.

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"*Exemplarisch, formularisch. Een hoop lol, de vorm hilarisch*"

De Formule, De Jeugd van Tegenwoordig

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Chapter 1
General introduction

"*Consciousness is a phase of mental life which arises in connection with the formation of new habits. When habit is formed, consciousness only interferes to spoil our performance*"

William Ralph Inge

Typically, during early stages of motor learning performers explore a variety of movement solutions in order to establish the most effective way to perform. They make a lot of errors and test different hypotheses to correct those errors, thus building up a declarative knowledge base about the movement (Masters & Maxwell, 2008; Maxwell, Masters, & Eves, 2003). With practice (or repetition), the declarative knowledge that was accumulated gradually is used less frequently. Rather than consciously thinking about '*what*' to do, associations between different aspects of the movements are developed and the performer can focus on '*how*' to do the movement. Eventually, after extensive practice, the motor skill is executed with minimal interference from conscious processes (e.g., Abernethy, Maxwell, Masters, van der Kamp, & Jackson, 2012; Beilock & Carr, 2004; Shiffrin & Schneider, 1977).

When under pressure, expert performers may fall back to the cognitive stage of learning during which performance was controlled by conscious processes in an effort to ensure successful outcomes (Masters & Maxwell, 2008). Ironically, conscious efforts to perform well can lead to significant deterioration in performance (see Beilock & Gray, 2007, for reviews; Christensen, Sutton, & McIlwain, 2014). Indeed, much research has accumulated to show that pressure manipulations or self-focus instructions can provoke people to consciously process their movements, which often results in performance breakdown (e.g., Beilock, Carr, MacMahon, & Starkes, 2002; Gray, 2004; Hardy, Mullen, & Jones, 1996; Hardy, Mullen, & Martin, 2001; Jackson, Ashford, & Norsworthy, 2006).

Different theories have been established to explain this phenomenon. For example, '*self-focus theory'* (Baumeister, 1984) suggests that skill breakdown under pressure occurs because pressure draws an individual's attention inwards to the process of motor control, which disrupts automatic motor processing and potentially impairs motor performance (Baumeister & Showers, 1986; Christensen et al., 2014). Masters (1992) extended this approach with the *'theory of reinvestment'*. The theory suggests that an individual's attention can be drawn inwards to process previously acquired declarative knowledge in order to consciously control movements online, which can disrupt automated components of motor performance. Masters, Polman, and Hammond (1993) further extended the theory of reinvestment by suggesting that individual differences exist in the propensity that people have to consciously control their movements online (see Masters & Maxwell, 2008, for a full elaboration of the theory or reinvestment). Almost a decade later, Wulf, McNevin, and Shea (2001) developed the '*constrained action hypothesis*', which proposes that "…trying to consciously control one's movements constrains the motor system by interfering with automatic motor control processes that would 'normally' regulate the movement" (p. 1144). Despite their differences, these theories all suggest that an inward focus of attention causes conscious movement control, which interferes with automatic motor processes.

1.1 Working memory

"*Working memory is the process of maintaining a limited amount of information in an active representation for a brief period of time so that it is available for use. Therefore, by definition, working memory includes those processes that enable us to hold in our 'mind's eye' the contents of our conscious awareness, even in the absence of sensory input*"

Courtney, Petit, Haxby, and Ungerleider (1998, p. 1819)

Working memory has been argued to mediate the interaction between conscious and unconscious processes (e.g., Baars & Franklin, 2003; Baddeley, 1993; Courtney et al., 1998; Crick & Koch, 1990). Working memory nowadays is generally referred to as the "blackboard" of the brain (Goldman-Rakic, 1992), where information can be stored and manipulated for a short period of time. Working memory is associated with a variety of complex cognitive processes, like

language, learning and reasoning (Baddeley, 2003; Gathercole, Brown, & Pickering, 2003; Goldman-Rakic, 1992; Kane et al., 2007; Kyllonen & Christal, 1990). It is therefore also central to processing and manipulating declarative information related to movements (Baumeister, Reinecke, Liesen, & Weiss, 2008).

The term '*working memory'* was first developed by Miller, Galanter, and Pribram (1960), and described as the "*memory for plans of future action"* (Constantinidis & Klingberg, 2016, p. 1). However, Atkinson and Shiffrin (1968) were the first to really start developing the concept of working memory as it is understood now (Spillers, Brewer, & Unsworth, 2012). Their '*multistore model of memory*' was proposed to consist of three stores: *sensory register*, *short-term memory* and *long-term memory*. The model describes information passing through these stores, starting with sensory memory in which information is detected and temporarily held. If attention is paid to this information, then it is passed on to the short-term memory store. The information reaches the long-term memory store if it is rehearsed, otherwise it is forgotten. Although ground-breaking, this model has received significant criticism (see Plancher & Barrouillet, 2019, for an overview). For instance, the idea that there is a single short-term store, which maintains memory items, processes other cognitive aspects, and is essential to get information to long-term memory, is unlikely. This is based on the fact that a patient (patient K.F.) with short-term memory damage was still able to process long-term memory information (Shallice & Warrington, 1970; Warrington & Shallice, 1969). Based on this, Baddeley and Hitch (1974) examined whether verbal reasoning (judging sentences to be true or false) was influenced by a concurrent memory load (maintenance of a digit sequence). They revealed that there was only minimal disruption of verbal reasoning, even when participants approached their memory load storage capacity. These results were the basis for the development of the '*multiple-component*' working memory model, in which a controlling central system is responsible for implementation and supervision of ongoing processes, while storage external slave systems deal with storage (Baddeley & Hitch, 1974).

The multiple-component model proposed by Baddeley and Hitch (1974) has become one of the most prominent models of working memory. This model consists of a *central executive,* which is responsible for attentional control, storage and decision making. The central executive is the most complex, but also most criticised,

component of the model (e.g., Baddeley, 1998; Duff, 2000; Just & Carpenter, 1992). The central executive has two slave systems; the *visuospatial sketch pad* and *phonological loop*. The visuospatial sketch pad is used to manipulate visual information (i.e., visuospatial working memory). The *phonological loop*, the best developed and most investigated system (Baddeley, 2012), is used to store and repeat auditory information (i.e., verbal working memory). Baddeley (2000) added a fourth system, which was called the *episodic buffer memory*. Initially, this system was described as the link between short- and long-term memory. Later, Baddeley updated the function of the *episodic buffer* by suggesting that it is a system that can hold short-term information and integrate it with information from the other systems and long-term memory (Baddeley, 2012) (see Figure 1.1).

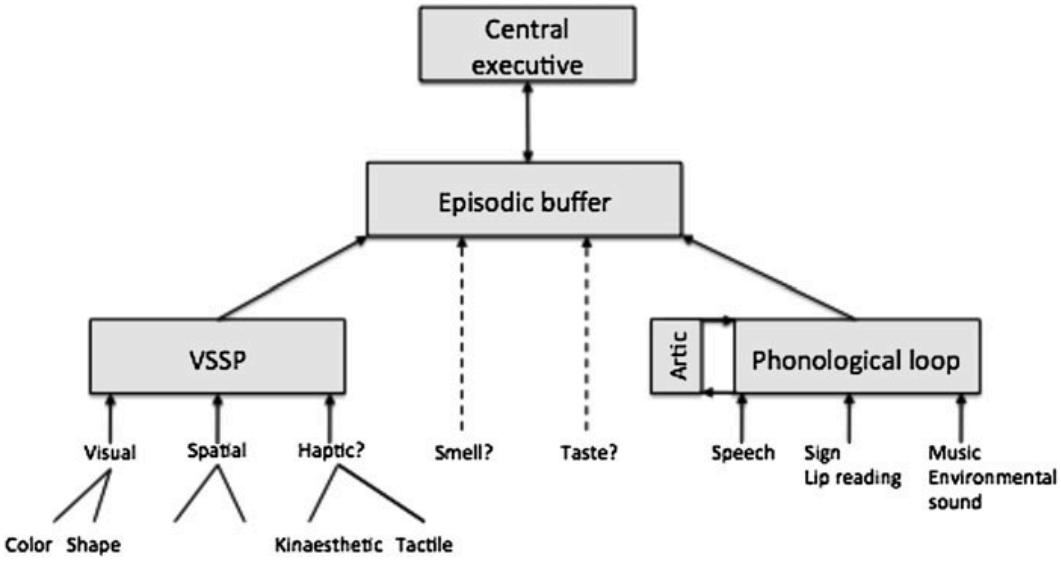

Figure 1.1 Newest working memory model (Baddeley, 2012, p. 23). Reprinted with permission from Baddeley (2012).

There are many other working memory models (e.g., Engle, Kane, & Tuholski, 1999; Ericsson & Kintsch, 1995; Oberauer, Süß, Wilhelm, & Sander, 2007); however, most of these models only explain some aspects of cognitive control (see Baddeley, 2012, for an overview of some models). This thesis will therefore focus on the multiple-component working memory model (Baddeley & Hitch, 1974), because this model is the most comprehensive and explains the concept of conscious control in motor skill practice and learning (Buszard, Farrow, et al., 2017).

1.1.1 Executive functions

Miyake et al. (2000) suggested that part of the central executive system of working memory is the executive functions. The executive functions are described as "*the general purpose control mechanisms that modulate the operation of various cognitive sub processes and thereby regulate the dynamics of human cognition*" (Miyake et al., 2000, p. 50).

The primary executive functions are shifting (also referred to as task switching or attentional switching), updating, and inhibition. Shifting is the ability to transfer attention backward and forward between several tasks or different streams of incoming information (Monsell, 1996). Updating is the ability to monitor and update working memory representations (Miyake et al., 2000; Morris & Jones, 1990). Specifically, updating consists of monitoring incoming information and, when needed, manipulating old information and new information in working memory (Miyake et al., 2000). This function is closely associated with working memory concepts (e.g., Jonides & Smith, 1997), and some researchers refer to updating by calling it working memory (e.g., Diamond, 2013). Inhibition is the intention to suppress irrelevant incoming information or pre-potent (automatized) responses (Diamond, 2013; Miyake et al., 2000). Although these executive functions are seen as independent entities, some aspects are related. For example, in order to switch, *old* processes need to be inhibited for the *new* processes to begin.

This thesis will treat the executive functions as the utilities that process information that is temporarily held in working memory. Consequently, working memory and its associated executive functions are considered to be the main cognitive processes involved in the conscious planning and execution of movements (e.g., Baumeister, Reinecke, Liesen, et al., 2008; Baumeister, Reinecke, & Weiss, 2008; Buszard, Farrow, et al., 2017; Diamond, 2000; Masters & Maxwell, 2004; Maxwell et al., 2003; Yogev-Seligmann, Hausdorff, & Giladi, 2008).

1.1.2 The role of working memory and executive functions in motor performance

Working memory is important for the conscious control of movement, because it deals with the manipulation and application of verbal declarative knowledge. Specifically, working memory is involved in processing visual, proprioceptive and

tactile sensory feedback about performance outcome (Maxwell et al., 2003). The processing of such feedback results in gathering information about movement solutions (i.e., hypothesis-testing). Working memory supervises and corrects utilization of this information when it is applied during movement execution. If the desired motor outcome is not achieved, the information is discarded or modified and eventually stored in long-term memory. The executive functions of working memory are thought to play a major role in processing the information (Baumeister, Reinecke, Liesen, et al., 2008; Diamond, 2000; Yogev-Seligmann et al., 2008), by updating old information with new information, switching between incoming information, and inhibiting irrelevant incoming information (Karatekin, Lazareff, & Asarnow, 2000; Miyake et al., 2000).

1.1.3 Individual differences in verbal-analytical engagement during motor performance

Individuals have been shown to have different propensities for engaging in conscious monitoring and control (i.e., movement specific reinvestment) during the motor learning process (e.g., Masters et al., 1993; Tse & van Ginneken, 2017). One explanation for this is that individuals have different amounts of working memory capacity, described as the capacity of information that can be temporarily held in short-term memory (e.g., Daneman & Carpenter, 1980; Engle, 2010; Kane, Bleckley, Conway, & Engle, 2001). These differences in working memory capacity may reflect differences in the ability for conscious control of movement (Buszard, Farrow, Zhu, & Masters, 2013, 2016). There is evidence that individuals with greater working memory capacity are more likely to accumulate verbal knowledge during motor performance (Buszard et al., 2013, 2016; Kane & Engle, 2002), visuo-motor learning (Christou, Miall, McNab, & Galea, 2016) and mathematical problem solving (Beilock & Carr, 2005; Beilock & Decaro, 2007).

Furley and Memmert (2012) found that basketball players with higher working memory capacity were more successful at blocking out irrelevant distraction (e.g., noise from an audience) during a computer-based tactical decision making task, compared to players with lower working memory capacity. Furthermore, in their second experiment, they revealed that ice-hockey players with higher working memory capacity had better tactical decision-making, independent of the instructions given by the coach prior to decision making. Players with lower

working memory capacity, however, tended to rely on instructions more, regardless of whether they were appropriate for task performance or not. The findings of Furley and Memmert (2012) suggest that people with higher working memory capacity are capable of processing more information, including verbal information. Furley and Memmert (2012) also argued that performers with high working memory capacity are better able to deal with situations involving high cognitive demand (see also Engle, 2002). This leads to the suggestion that higher working memory capacity is associated with higher working memory activity. In other words, people with high working memory capacity are more inclined to actively process information. Buszard et al. (2013) found that higher working memory capacity was associated with worse performance of a tennis hitting task, whereas lower working memory capacity was associated with better performance. Beilock and Carr (2005) found similar results for mathematical problems under pressure. Buszard et al. (2013) suggested that participants with higher working memory capacity are more likely to use complex rules to resolve motor problems. However, when pressure depletes working memory functions, performers are no longer able to process these complex rules. However, participants with low working memory capacity might process less complex rules, which are less affected when working memory is depleted under pressure.

In summary, research suggests that people with high working memory capacity tend to use their working memory more, which might result in better performance in tasks (including motor tasks) that are cognitively demanding. The performance of working memory and executive functions is, however, influenced by anxiety, which might increase the chances of skill breakdown under pressure in performers with high working memory capacity (see Buszard, Masters, & Farrow, 2017, for a review on working memory capacity in sports). Hence, if motor skills are acquired without a need for working memory activity, reduced verbal-analytical processing will occur (Maxwell et al., 2003). This means the performer is less likely to depend on their working memory capacity, and thus the chances of skill breakdown are lower (Maxwell et al., 2003).

1.2 Implicit motor learning

Implicit motor learning is thought to result in motor performance that occurs without the need to access conscious processes, thus, reducing dependency on working memory activity (Maxwell et al., 2003; Poolton, Maxwell, Masters, & Raab, 2006).

Reber (1967) first described the term *implicit learning* when he found that people could learn artificial grammars without being aware that they were learning them or of the underlying rule structures that guide their creation. Specifically, participants were asked to rote learn sequences of letters generated by a complex Markovian rule. After learning the sequences (exemplars), participants were surprisingly accurate at determining whether a new letter sequence was grammatically correct (i.e., was generated by the Markovian rule), despite having little or no conscious insight into how they made their decisions or why they were correct. Although studies have suggested that other factors may contribute to the ability to make correct judgments of grammaticality, there seems little doubt that unconscious knowledge plays a powerful role (Dulany, Carlson, & Dewey, 1984; Perruchet & Pacteau, 1990).

Early evidence that motor behaviours could be learned implicitly came in the form of the serial reaction time task (e.g., Nissen & Bullemer, 1987) and the continuous tracking task (e.g., Green & Flowers, 1991; Pew, 1974; Wulf & Schmidt, 1997; Zhu et al., 2014). Serial reaction time tasks, for example, require participants to make button presses (motor responses) in a seemingly random order. In truth, the button presses occur in a recurring sequence, which is generally not noticed by participants. Nevertheless, the motor responses of participants (button presses) become faster and faster, suggesting that they have learned the sequence implicitly (e.g., Nissen & Bullemer, 1987). Continuous tracking tasks require participants to track a moving target with a cursor. The target moves in an apparently random waveform pattern across a screen and consists of three segments, one of which (usually the middle) is not random, but is continually repeated on each trial. Although participants are unaware of the repeated segment, their motor performance (tracking) improves compared to the two segments for which the waveform pattern is always different (e.g., Pew, 1974; Wulf & Schmidt,

1997; Zhu et al., 2014). Green and Flowers (1991) used a different continuous task, in which participants had to visually track a ball and catch it with a cursor controlled by a joystick. The path of the ball included *glitch* or *fade* features. The explicit group received instructions that made them aware of these features, whereas the implicit group did not. Green and Flowers (1991) revealed that the implicit group performed overall better on the motor task, with different joystick movement patterns compared to the explicit group.

These studies suggest that performance of simple motor tasks can become more efficient without the learner having explicit knowledge or awareness of what is being learned; however, improvements in efficiency in both paradigms are primarily a consequence of the participant acquiring implicit knowledge of the recurring sequence or pattern, rather than the participant acquiring better ability to move.

Masters (1992), however, proposed that movements themselves can be acquired or improved implicitly. He showed that it is possible to learn complex movements implicitly, without building up explicit knowledge about how the movements are carried out. One group of participants practiced a golf putting task using instructions about how to execute the movements correctly (explicit motor learning). A second group of participants practiced without instructions, but instead engaged in a concurrent secondary task (a random letter generation task) that was designed to suppress working memory involvement during learning (implicit motor learning).[1] A third group of participants neither received instructions about the movements nor performed a secondary task (discovery learning).[2] Putting performance of all groups improved over 400 trials, although the implicit motor learning group had a slower rate of learning. Following training, however, participants in the implicit motor learning group reported the least amount of verbal declarative knowledge compared to the other two groups. In addition, they displayed performance that was immune to psychological pressure, whereas the explicit motor learning group and the discovery motor learning group showed a

[1] Verbal secondary tasks, such as random letter generation, use up working memory resources, which leaves little/no capacity for verbal-analytical engagement in motor control, therefore promoting implicit motor learning (e.g., MacMahon & Masters, 2002; Masters, 1992).

[2] Discovery learning typically occurs if people are not prevented/discouraged from testing different hypotheses to establish correct movement solutions (Masters, 1992).

reduction in performance. These results show that accumulation of verbal declarative knowledge is not necessary for motor learning to occur and in fact might impair performance under pressure. However, some researchers have suggested that despite the control conditions included in the Masters (1992) experiment, it is not possible to be certain that performance by implicit motor learners was immune to pressure, because the putting task became easier when the secondary task load was dispensed with during the pressure manipulation. Hardy et al. (1996) and Mullen, Hardy, and Oldham (2007), however, replicated and extended the experiment by Masters (1992), with the same results. Hardy et al. (1996), for example, included an implicit motor learning group that continued to perform the secondary task during a pressure manipulation. They found that implicit motor learners in this group were also immune to pressure. It is worth noting that Bright and Freedman (1998) had identical reservations, which they examined in an identical manner to Hardy et al. (1996). Bright and Freedman (1998), however, did not find that performance by the implicit learners was immune to pressure when they continued to perform the secondary task under pressure. There are, however, numerous inconsistencies in the Bright and Freedman (1998) experiment, which call into question the veracity of their findings.

Performance of a cognitive secondary task while learning a movement comes with a number of limitations. Not surprisingly, studies have revealed that the secondary task reduces the learning rate. Maxwell, Masters, and Eves (2000) imposed a secondary task during 3000 trials of golf putting. Participants learned implicitly, but their rate of learning was slower than participants who learned by discovery (although in a delayed retention test, during which the secondary task was not imposed, performance was not significantly different). Secondary tasks are also difficult to enforce. Participants often will fail to process both the primary task and the secondary task in parallel, instead processing them serially (especially if they become mentally fatigued). A consequence of serial processing is that the participant has an opportunity to acquire knowledge about the primary task because, at least momentarily, working memory is not otherwise engaged. It is also difficult to apply the secondary task paradigm in practical settings. For instance, it would be difficult for a coach to ensure that all individuals in a team perform the secondary task during practice. Hence, other implicit motor learning paradigms have been

established, which are more likely to increase successful motor performance and are easier to apply in practical settings (Masters, 2000).

1.2.1 Error-reduced learning

When learning occurs with minimal errors, it is more likely that learning occurs passively, without the involvement of conscious processes (Prather, 1971). Maxwell, Masters, Kerr, and Weedon (2001) therefore predicted that reducing errors during learning would decrease conscious engagement in the motor skill, thereby promoting implicit motor learning. Maxwell et al. (2001) investigated this by conducting a golf putting learning task, which either started with a target being close to the performer (error-reduced learning group) or far away from the performer (error-strewn learning group). During practice, performers in the error-reduced learning group gradually moved further away from the target, whereas the performers in the error-strewn learning group gradually moved closer to the target. Those in the error-reduced learning group reported less hypotheses testing during learning and performed at a higher level under dual-task conditions, compared to those in the error-strewn learning group. Maxwell et al. (2001) argued that this occurred because working memory was not needed for the motor task, and therefore was freely available for tone counting. Error-reduced learning has been shown to be beneficial not only for beginners in a motor task, but also for athletes (e.g., Gabbett & Masters, 2011), children (e.g., Masters, van der Kamp, & Capio, 2013), older adults (e.g., Chauvel et al., 2012) and individuals with lower cognitive abilities (e.g., Alzheimer's disease or cerebral palsy) (e.g., Chauvel et al., 2018; van Abswoude, Santos-Vieira, van der Kamp, & Steenbergen, 2015).

However, there are also studies that do not report evidence for the efficacy of error-reduced learning (e.g., Clare & Jones, 2008; Kessels, Te Boekhorst, & Postma, 2005; Ong, Lohse, & Hodges, 2015; Prather, 1971; Sanli & Lee, 2014). For example, Ong et al. (2015) revealed that participants throwing darts at a large target (i.e., error-reduced) did not differ in performance (radial error) during practice (90 trials) or under a secondary task load, compared to participants throwing at a small target (i.e., error-strewn). However, Ong et al. (2015) did not introduce incremental changes in target size in their experiment, as has typically been done in these kinds of experiments. Consequently, to assess performance during the practice phase is uninformative, because participants were throwing at

differently sized targets. Relatedly, neither group shows a typical power law learning curve during practice, which is surprising (especially for the small target condition). Second, the lack of differences in performance accuracy during the post-test and delayed retention test are perhaps not surprising, given that error-reduced participants practiced throwing to a larger target than the error-strewn participants; transfer to throwing at a bullseye was thus more difficult for them. Consequently, the fact that they perform as well as the error-strewn participants in the post-test and delayed retention test may indicate that there was a learning advantage of error-reduced learning. Third, performance by neither group was disrupted by the secondary task, suggesting that either the secondary task was too easy or that participants in both conditions learned with few demands on working memory, indicative of implicit motor learning. Ong et al. (2015) do not discuss this possibility. Sanli and Lee (2014) did utilise incremental changes, both in target size (Experiment 1) and distance to the target (Experiment 2), but they also found minimal evidence to support previous claims that error-reduced approaches cause implicit motor learning. Sanli and Lee (2014) suggested that the timing of errors in relation to task difficulty is likely to be a critical factor in motor learning.

1.2.2 Analogy learning

Analogies use familiar concepts to create an understanding of the to-be-performed concepts. For example, the road sign "*merge like a zip*" creates a general understand for drivers of how they should merge onto a motorway. Masters (2000) proposed that analogies can be employed to cause implicit motor learning, by using one 'message' that connects a movement to a well-known concept. Liao and Masters (2001) tested this claim by instructing table tennis novices to perform a topspin forehand using the analogy of "strike the ball while bringing the bat up the hypotenuse of a triangle". No other instructions were given during the practice of the topspin. The analogy group performed better under dual-task load and under pressure following practice, compared to a group that had received explicit rules about how to execute their movements correctly (i.e., explicit motor learning). Evidence supporting the efficacy of analogy learning has accumulated for different populations, such as for typically developing children (e.g., Tse, Fong, Wong, & Masters, 2017), children with autism (e.g., Tse & Masters, 2019), stroke patients (e.g., Kleynen et al., 2019), and older adults (e.g., Tse, Wong, & Masters, 2017).

However, there are also studies that were unable to support analogy learning (e.g., Bobrownicki, MacPherson, Coleman, Collins, & Sproule, 2015; Koedijker, Oudejans, & Beek, 2008). Koedijker et al. (2008), for example, revealed that analogy motor learning did not cause better performance under pressure compared to explicit motor learning, after many learning trials. Additionally, they also revealed that the effectiveness of analogy learning slows earlier during practice, compared to explicit motor learning. Koedijker et al. (2008) suggested that this occurred because error-detection and correction is reduced during analogy learning, which might reduce motivation to keep improving on the motor task.

1.2.3 Subliminal feedback

Maxwell et al. (2003) hypothesised that withholding visual feedback of performance outcome (e.g., absence of knowledge of where a ball comes to rest relative to the target, during golf putting) would reduce verbal-analytical engagement during practice, because participants would have little or no information upon which to base adjustments of technique. However, performers for whom visual feedback was withheld accumulated explicit knowledge associated with other feedback sources (e.g., proprioceptive and tactile). Therefore, Masters, Maxwell, and Eves (2009) investigated whether it was possible to provide visual feedback about performance outcome without performers being aware of the information (i.e., subliminal feedback). Two thresholds of awareness have been demonstrated, an objective and a subjective threshold (Cheesman & Merikle, 1984). The subjective threshold occurs when a person is unaware of the information that is being presented, but discriminates the information better than chance. The objective threshold occurs when a person is unaware of the information that is presented, and cannot discriminate the information better than chance. Masters et al. (2009) used a three-field tachistoscope to present visual outcome feedback to participants practicing a golf putting task. After each practice trial, they viewed a visual representation of the final resting position of the golf ball relative to the target, which was presented at a subjective threshold of awareness, an objective threshold of awareness or a supraliminal threshold (i.e., above the threshold of awareness). Masters et al. (2009) argued that performance would not improve in the objective threshold condition where participants had no conscious or nonconscious knowledge of performance outcome, and it would improve in the

supraliminal threshold condition, where participants had full conscious knowledge of performance outcome. Crucially, Masters et al. (2009) hypothesised that in the subjective threshold condition participants would be unable to test explicit hypotheses about their performance (and make appropriate adjustments of technique) if they were unaware of the outcome feedback, but nevertheless they would use the outcome feedback subconsciously to improve their performance (implicit motor learning). As expected, performance accuracy improved significantly in the supraliminal and subjective threshold conditions, but not in the objective threshold condition. As hypothesised, participants reported very little explicit knowledge about their movements (examined by verbal protocols),[3] suggesting that they were unable to test explicit hypotheses about their performance (and make appropriate adjustments of technique) and thus learned implicitly. However, this was also the case for participants in the supraliminal condition despite the fact that they were fully aware of the outcome feedback. Masters et al. (2009) concluded that hypothesis testing was disrupted by the distractions associated with peering into the tachistoscope after every trial. Nevertheless, these findings do reveal that detecting performance outcome is necessary for learning, but being aware of the outcome is not.

1.2.4 The advantages and disadvantages of learning implicitly

Anxiety can increase self-focus and reinvestment of verbal-analytical knowledge (Baumeister, 1984; Masters, 1992). Reinvestment of verbal-analytical knowledge takes up working memory resources, which can disrupt normally efficient motor behaviours (Masters, 1992; see Masters & Maxwell, 2008 for a review). Consequently, if motor performance is guided by verbal-analytical processes (i.e., explicitly learning), the literature assumes that it will be disrupted under pressure (e.g., Hardy et al., 1996; Liao & Masters, 2001; Masters, 1992; Zhu, Poolton, Wilson, Maxwell, & Masters, 2011). Implicit motor learning, however, occurs with reduced verbal-analytical processes, and is therefore less likely to result in reinvestment of verbal-analytical knowledge under pressure (e.g., Hardy et al.,

[3] Verbal protocols required participants to write down any rules, knowledge or methods they recalled using during the golf putting practice (Masters et al., 2009).

1996; Liao & Masters, 2001; Masters, 1992; Zhu, Poolton, Wilson, Maxwell, et al., 2011).

Implicit motor learning methodologies have not only been investigated in the context of psychological pressure, but also physiological fatigue (Masters, Poolton, & Maxwell, 2008; Poolton, Masters, & Maxwell, 2007) and decision-making (Masters, Poolton, Maxwell, & Raab, 2008; Poolton et al., 2006). Furthermore, implicit motor learning has been shown to be an efficient way of learning (e.g., Masters & Maxwell, 2004; Masters, van Duijn, & Uiga, 2019), which is independent of working memory capacity (e.g., Capio, Poolton, Sit, Eguia, & Masters, 2013; Capio, Sit, Abernethy, & Masters, 2012; Steenbergen, van der Kamp, Verneau, Jongbloed-Pereboom, & Masters, 2010) and age (Chauvel et al., 2012). The benefits of learning implicitly have been established in a broad range of sports, including golf putting (e.g., Lam, Maxwell, & Masters, 2010), football (Savelsbergh, Cañal-Bruland, & van der Kamp, 2012), table tennis (Koedijker et al., 2008; Liao & Masters, 2001), rugby (Masters, Poolton, Maxwell, et al., 2008), basketball (e.g., Lam, Maxwell, & Masters, 2009b), as well as in non-sport movement settings, like balance tasks (e.g., Orrell, Eves, & Masters, 2006a). Additionally, it has been shown to be beneficial for patient groups like children with motor development coordination disorders (e.g., Candler & Meeuwsen, 2002), Parkinson's patients (e.g., Masters, MacMahon, & Pall, 2004), stroke patients (e.g., Orrell, Eves, & Masters, 2006b; Orrell, Masters, & Eves, 2009), and cerebral palsy patients (van Abswoude et al., 2015). Finally, implicit motor learning has also been shown to be efficient for laparoscopy (e.g., Zhu, Poolton, Wilson, Hu, et al., 2011) and surgery (e.g., Masters, Lo, Maxwell, & Patil, 2008).

Implicit motor learning paradigms (e.g., dual-task, analogy, error reduced learning) have been proven effective in many studies (see Masters et al., 2019). However, they are indirect (i.e., behavioural) methods of supressing working memory involvement in learning and, therefore, leave an opportunity for people to accumulate task relevant verbal knowledge. Indeed, it has been shown that people with a high propensity to engage in conscious monitoring and control of their movements (movement specific reinvestment) tend to accumulate more task relevant knowledge, and are more likely to use that knowledge when performing under pressure (Poolton, Maxwell, & Masters, 2004). Each paradigm also has its

own particular idiosyncrasies. For example, errorless learning is not possible in every environmental setting and an analogy may be meaningful for some people but not others (Masters et al., 2019).

1.3 Direct suppression of verbal-analytical engagement

Researchers have tried to establish different methods by which to directly suppress working memory in order to promote implicit motor learning. MacMahon and Masters (2002), for example, tried to disrupt one of the slave systems of working memory, the phonological loop. The phonological loop is responsible for storage and rehearsal of speech based information, and can be suppressed by articulatory suppression (Baddeley, Lewis, & Vallar, 1984).[4] MacMahon and Masters (2002) predicted that suppression of the phonological loop would prevent participants from storing and rehearsing speech based information associated with motor performance, without the reduced learning rate that often accompanies implicit motor learning via demanding secondary tasks, such as random letter generation. However, solely suppressing the phonological loop did not promote implicit motor learning. Participants learned the motor task without any disruption to the rate of learning, but not implicitly. MacMahon and Masters (2002) concluded that a less demanding secondary task load, which only suppresses the phonological loop, is not sufficient to reduce accumulation of explicit, declarative knowledge.

Zhu et al. (2015) adopted a different approach to directly suppress verbal-analytical engagement in motor performance. They applied transcranial Direct Current Stimulation (tDCS) over the left dorsolateral prefrontal cortex in an effort to suppress verbal working memory activity during motor practice. During tDCS an electric current passes between a negative electrode and a positive electrode (Davis, 2013), causing the brain cells close to the negative (cathode) electrode to become less active, and the cells close to the positive (anode) electrode to become more active. Zhu et al. (2015) found that real stimulation of the left dorsolateral prefrontal cortex suppressed verbal working memory activity compared to sham stimulation, with evidence of implicit motor learning suggested by stable performance under dual-task conditions.

[4] Articulatory suppression requires a performer to repeat a word or nonsense syllable continuously (e.g., two words every second, MacMahon & Masters, 2002).

Some researchers have argued that tDCS is a form of neurodoping, since it is a potential performance-enhancing method (Davis, 2013). Neurofeedback has therefore been proposed as an alternative method to manipulate cortical activity during performance (see Cooke, Bellomo, Gallicchio, & Ring, 2018, for a review). Neurofeedback provides individuals an opportunity to learn how to produce patterns of cortical activity (i.e., to activate/deactivate a certain frequency for a certain region of the brain) that are reflective of expertise. It is hypothesised that this speeds up learning by encouraging adoption of neural patterns that normally develop over years of practice. Performers are provided with visual or auditory feedback about their brain activity and are instructed to, for example, lower a bar under a specific threshold line (visual feedback) or to silence a tone (auditory feedback). This feedback training can occur prior to motor practice or in combination with motor performance (i.e., the movement will be performed when the tone is silent). Ros, Munneke, Parkinson, and Gruzelier (2014) revealed that neurofeedback training led to greater implicit motor learning of a serial reaction time task. Ring, Cooke, Kavussanu, McIntyre, and Masters (2015) introduced neurofeedback training for learning a more complex motor task, golf-putting. They revealed that participants were able to control their cortical activity after the neurofeedback training; however, this did not lead to a better rate of learning or better performance under pressure, compared to a control condition (false neurofeedback training). Although tDCS and neurofeedback training are promising methods of implicit motor learning, they are not always easy to apply and are not cost effective. This thesis therefore explores alternative methods of direct working memory suppression that might be more feasible.

1.3.1 Working memory fatigue

Fatiguing working memory before motor learning could potentially be an alternative method by which to cause direct suppression of working memory, thus and promote implicit motor learning. The literature has described cognitive fatigue as a state of fatigue occurring after prolonged periods of cognitively demanding performance (e.g., Boksem, Meijman, & Lorist, 2005; Borragan, Slama, Destrebecqz, & Peigneux, 2016; Marcora, Staiano, & Manning, 2009; Trejo, Kubitz, Rosipal, Kochavi, & Montgomery, 2015). Accordingly, previous studies have revealed that cognitive fatigue suppresses working memory functions (e.g.,

executive functions) (e.g., Ishii, Tanaka, & Watanabe, 2014; Kathner, Wriessnegger, Muller-Putz, Kubler, & Halder, 2014; Kato, Endo, & Kizuka, 2009; Tanaka, 2015; Tanaka et al., 2012; van der Linden, Frese, & Meijman, 2003). Van der Linden et al. (2003) found that cognitive fatigue affected task engagement and executive control[5] of behaviour during the performance of a complex computer task. Reduced executive control caused reduced goal-directed behaviour, resulting in more automatic regulatory processes. Wolfgang and Schmitt (2009) revealed that prolonged performance of a Stroop task caused cognitive fatigue, which reduced performance. The Stroop task (Stroop, 1935) requires performers to name the colour in which colour words are written, which requires performers to consciously inhibit their automatic tendency to read the written word. Hence, both these studies suggest that cognitive fatigue reduces working memory functions for conscious goal-directed behaviour, promoting more automatized behaviour.

Borragan et al. (2016) also suggested that cognitive fatigue influenced conscious control. Borragan et al. (2016) examined performance of a serial reaction time task (SRTT) by participants in a cognitive fatigue group or a non-cognitive fatigue group. Borragan et al. (2016) found that cognitive fatigue led to improved learning of the sequence compared to no fatigue. They argued that cognitive fatigue reduced conscious top-down interference by executive functions, which was beneficial for implicit learning.

Taken together, these findings imply that cognitive fatigue promotes more automatized, implicit, performance of simple motor tasks. This thesis examines whether cognitive fatigue also causes implicit learning of complex motor tasks, by reducing working memory activity and thereby suppressing verbal-analytical processing of movements.

1.3.2 Hand contraction protocols

Suppressing activity in the left hemisphere by promoting right hemisphere activity may reduce verbal-analytical processing during practice and thereby promote implicit motor learning. Steenberg and van der Kamp (2008) reported evidence that

[5] Executive control, which is closely associated with executive functions (e.g., Miyake et al., 2000), refers to the capacity to control perceptual and motor processes in order to respond to new or changing demands (e.g., Baddeley & Logie, 1999).

favours this suggestion. Consistent with unaffected participants, they showed that participants with right-hemisphere damage were worse at soccer dribbling (i.e., slower) when they were asked to concentrate on the contact between their foot and the ball (task-relevant focus of attention) compared to when they were asked to monitor a sequence of words (task-irrelevant focus of attention). However, participants with damage to the left-hemisphere were unaffected by task-relevant focus compared to task-irrelevant focus. Steenberg and van der Kamp (2008) argued that task-relevant focus of attention induced cortical activity in the left hemisphere, which is used for verbal-analytical processing of movement. Performance by healthy participants and participants with right-hemisphere damage was therefore disrupted by task-relevant focus of attention because their intact left hemisphere could engage in disruptive verbal-analytical processing of performance. Performance by participants with left-hemisphere damage, on the other hand, was not disrupted by task-relevant focus of attention because the damage prevented them from engaging in disruptive verbal-analytical processing of performance.

Van der Kamp, Steenbergen, and Masters (2018) reported similar results for young individuals with right hemisphere disturbance (left unilateral cerebral palsy) compared to left hemisphere disturbance (right unilateral cerebral palsy). Van der Kamp et al. (2018) asked the patients groups (i.e., right or left unilateral cerebral palsy) and a control group (i.e., healthy children) to practice a shuffleboard task[6] using prism lens glasses to create a visual in the target, either to the left or the right. Each group was divided into an instructed group or an uninstructed group. The instructed group was aware of the bias and instructed how to adapt their performance in order to deal with it (explicit instructions), but the uninstructed group was not aware of the visual shift bias and received no instructions (discovery learning). Rate of adjustment in aiming accuracy while wearing the prism glasses was used as a measure of explicit learning and the size of the after-effect (when the glasses were removed) was used as a measure of implicit learning. The results revealed that the capacity for implicit learning did not differ between any of the groups, but that participants in the right cerebral palsy group needed significantly more trials to adjust to the visual bias than the left cerebral palsy group when no

[6] The shuffleboard game is a traditional Dutch board game, in which a wooden disk has to be shuffled to a target at the far end of a wooden board.

instructions were provided. This suggests that left hemisphere disturbance causes reduced explicit motor learning.

Hand contractions are potentially a method by which to create the same effect without the need for brain damage. This idea leverages the contralateral coupling between the hands and the brain (i.e., the brain area controlling the right hand resides in left hemisphere, and vice-versa) to create hemisphere-specific priming. Hemisphere-specific priming implies that activating one hemisphere creates an advantage for any processes that rely on that hemisphere (Hellige, 1993). Therefore, squeezing the right hand should prime the left hemisphere, which is responsible for verbal-analytical processes, and squeezing the left hand should prime the right hemisphere, which is responsible for visual-spatial processes (De Renzi, 1982). In cognitive psychology, the effects of hand contractions have been extensively studied in approach and avoidance behaviour, (e.g., Harmon-Jones, 2006) aggression (Harmon-Jones, Sigelman, Bohlig, & Harmon-Jones, 2003; Peterson, Shackman, & Harmon-Jones, 2008), emotions (Schiff, Guirguis, Kenwood, & Herman, 1998), memory storage and retrieval (Propper, McGraw, Brunye, & Weiss, 2013) and line bisection (Goldstein, Revivo, Kreitler, & Metuki, 2010). All of these studies suggest that cognitive processes can be manipulated by using hand contractions to activate the contralateral hemisphere. Consequently, pre-performance left hand-contractions may cause hemisphere-specific priming by activating the right hemisphere and suppressing left hemisphere activity (Beckmann, Gröpel, & Ehrlenspiel, 2013; Gröpel & Beckmann, 2017).

Beckmann et al. (2013) and Gröpel and Beckmann (2017) were the first to implement pre-performance hand contraction protocols in a sport context. Both studies revealed that athletes performing left-hand contractions were less likely to display skill failure under pressure, whereas athletes performing right hand contractions were more likely to. For example, Beckmann et al. (2013), instructed taekwondo athletes to perform kicks at a sandbag as fast as possible, under normal and pressured conditions. The normal condition was performed first and followed by a right-hand or left-hand contraction protocol for 30 sec. Thereafter, the athletes performed the kicking task under pressure caused by an audience watching the athletes as they performed the penalty kicks. The results showed that the athletes tended to fail under pressure after performing the right-hand contractions; however,

the athletes performing the left-hand contractions did not. The authors concluded that left-hand contractions led to reduced verbal engagement during motor task performance, compared to right-hand contractions. However, this was only speculation, as cognitive processes were not assessed.

Other studies, however, have examined the potential effects of hand contraction protocols on cognitive processes (Cross-Villasana, Gropel, Doppelmayr, & Beckmann, 2015; Gable, Poole, & Cook, 2013; Harmon-Jones, 2006; Schiff et al., 1998). Most of these studies revealed that unilateral hand contractions led to higher cortical activity in the contralateral brain hemisphere (Gable et al., 2013; Harmon-Jones, 2006; Schiff et al., 1998). However, Cross-Villasana et al. (2015) revealed increased cortical activity over the bilateral motor area during contraction of either hand. Additionally, they reported that immediately after left-hand contractions a global state of reduced cortical activity occurred. A possible explanation for the reduced likelihood of skill failure under pressure is, therefore, that cortical activity is high during hand contractions, but reduced cortical activity immediately afterwards manifests in reduced verbal-analytical activity.

To conclude, previous studies suggest that left-hand contractions reduce the likelihood of skill failure under pressure among experts, but none have examined novice motor learning and performance. Furthermore, the studies of experts lack a control (no-hand contraction) condition. Finally, brain activity (as described above) has only been examined during performance of the hand contraction protocols or just after when participants are doing nothing. In order to establish whether left-hand contraction protocols promote implicit motor learning, more studies are required to examine the effects of hand contractions on cognitive processes when participants are performing a motor task, compared to a control condition.

1.4 Measuring implicit motor learning

There are different ways to gauge the extent to which learning has occurred implicitly or explicitly. Typically, performance during dual-task conditions is considered to be an indirect estimate of conscious involvement in motor performance (e.g., Lam, Maxwell, & Masters, 2009a; Liao & Masters, 2001; Masters, 1992; Maxwell et al., 2001). If motor performance is guided by verbal-analytical processes, the literature assumes that it will be disrupted in dual-task

conditions. Zeithhamova and Maddox (2006), for example, used category learning to show that a secondary task only interferes with learning that has occurred explicitly – a style of learning that relies on working memory and selective attention. Zeithhamova and Maddox (2006) argued that explicit learning systems use working memory, so a concurrent secondary task that also uses working memory, can exceed the limited resources of working memory, causing performance of the explicit task to be disrupted. Implicit learning systems, however, do not rely so much on working memory, so concurrent secondary tasks that use working memory are less likely to exceed the limited resources of working memory, and thus do not disrupt performance of the implicit task. Masters and colleagues reported this for explicit and implicit motor learning. They showed that skills learned explicitly, using working memory for verbal-analytical processing, were disrupted under dual-task conditions, whereas, skills acquired implicitly were robust in dual-task conditions (e.g., Maxwell et al., 2003).

Movement kinematics have also been examined under dual-task and high-pressure conditions to provide another means of estimating the extent of conscious involvement in motor performance (Cooke et al., 2014; Cooke, Kavussanu, McIntyre, Boardley, & Ring, 2011; Cooke, Kavussanu, McIntyre, & Ring, 2010; Lam et al., 2009a; Lohse, Sherwood, & Healy, 2010; Malhotra, Poolton, Wilson, Omuro, & Masters, 2015; Maxwell et al., 2003; Munzert, Maurer, & Reiser, 2014). Based on the idea that implicit processes are relatively effortless and automatic (e.g., Oliveira & Goodman, 2004; Wulf & Lewthwaite, 2010), researchers have reasoned that kinematics should be more fluent and consistent within and between-trials when movements are performed in an implicit compared to an explicit manner (e.g., Maxwell et al., 2003). Furthermore, if movement kinematics are disrupted upon transition from single-task to dual-task or from low-pressure to high-pressure conditions, researchers have reasoned that this could reflect reinvestment in verbal-analytic processes. For instance, Cooke et al. (2010) revealed that novice golfers increased lateral putter-head acceleration from low-pressure to high-pressure conditions. This resulted in disruptions of their putter face angle and was revealed as a partial mediator of the decline in performance that was evident from low-pressure to high-pressure conditions. These findings can be interpreted as kinematic evidence of reinvestment under pressure. Additionally, Maxwell et al. (2003)

revealed that participants who learned a golf putting task with high dependence on working memory (i.e., explicit motor learning) performed the golf swing less smoothly and more jerkily when under a secondary task load after practice (i.e., transfer task) compared to a participants who learned without dependence on working memory (i.e., implicit motor learning). Maxwell et al. (2003) determined kinematic smoothness by calculating changes in acceleration (i.e., smoothness) and the root mean square jerk (i.e., fluidity) of the swing. These findings have been interpreted as kinematic evidence of reinvestment under dual-task performance.

Changes in technique or movement solutions are of interest because when a performer is frequently making adjustments to technique or attempting novel movement solutions, it is likely that the performer is testing hypotheses on how to improve the motor skill (Maxwell et al., 2001; Poolton, Masters, & Maxwell, 2005). Maxwell et al. (2001), for example, revealed that participants who learned a golf putting task with high dependence on working memory (i.e., error-strewn) made more technique changes and reported more verbal rules about how to perform the task, compared to participants who learned with low dependence on working memory (i.e., error reduced). Maxwell et al. (2001) suggested that more technique changes reflected more hypothesis testing, which then generates more verbal knowledge of the motor skill. Besides examining changes in technique, it is also common to simply ask participants about how they performed the task (e.g., MacMahon & Masters, 2002; Masters, 1992). Participants are normally required to report any rules, knowledge, or methods they had used during practice or performance. While such self-report measures can be informative, verbal reports are subjective post hoc measures and may not reflect the exact level of conscious involvement in motor performance. Fortunately, probe reaction times may provide a more objective measure. The probe reaction time paradigm typically involves measuring a simple verbal reaction to an auditory tone that occurs during preparation for or execution of the motor task (Lam et al., 2010; Wulf & Lewthwaite, 2010). Studies have revealed that probe reaction times are slower when performers have high verbal-analytical engagement in their movements, presumably because conscious processing taxes working memory resources and thus impedes the ability of working memory to identify and respond to the auditory tone (e.g., Lam et al., 2010; Wulf & Lewthwaite, 2010). The probe reaction time

paradigm has the benefit of measuring attention allocation during different aspects of motor execution (e.g., at movement initiation versus during movement execution); however, it cannot indicate the precise content of information that was consciously processed. The measures described above can be considered to be behavioural markers of conscious movement processing. Recently, psychophysiological measures have been implemented to further determine the level of conscious processing of motor task performance. These measures include cardiac activity, electromyography (EMG) and electroencephalography (EEG).

1.4.1 Cardiac activity

Measures of cardiac activity during motor performance have been shown to distinguish experts from novices (Cooke et al., 2014). Since experts and novices typically differ in their conscious investment in movement control (i.e., novices engage in more conscious processing than experts), it is possible that expert and novice differences in cardiac activity represent their different conscious processing levels. For example, Neumann and Thomas (2009) revealed that experts showed greater deceleration in heart rate during the final seconds preceding golf putts when compared to novices. They argued that this occurred because experts perform skills in a more automatic manner, with less conscious involvement. Cooke et al. (2014) replicated this finding and argued that this might have occurred because experts engage in more external information processing when planning the movement (Brunia, 1993). However, the heart rate deceleration was not associated with whether putts were holed or missed, revealing that heart deceleration is not a sensitive enough measure for prediction of performance outcome (Konttinen, Lyytinen, & Viitasalo, 1998).

1.4.2 Electromyography

Increased muscle activity and contraction duration is evident under high pressure conditions compared to low pressure conditions (Cooke et al., 2010; Weinberg & Hunt, 1976). For example, Weinberg and Hunt (1976) revealed longer contraction (i.e., higher activity) of the extensor carpi radialis (triceps) and bicep brachii (biceps) when pressure was felt during ball throwing performance. They concluded that this may have occurred because of an inward focus of attention when under pressure, implying that there is reduced neuromuscular efficiency when pressure is felt. In

support of this conclusion, more recent research comparing internal and external attentional foci has revealed that directing attention to external information (e.g., the object used for performance) is associated with reduced muscular activity and may encourage more automatized performance (Lohse et al., 2010; Vance, Wulf, Tollner, McNevin, & Mercer, 2004; Zachry, Wulf, Mercer, & Bezodis, 2005). For example, Lohse et al. (2010) revealed reduced muscle activity when participants performed a dart throw task with an external focus of attention (i.e., focus on the dart) compared to an internal focus of attention (i.e., focus on your arm). Accordingly, the amount of task-related muscular activation during motor performance could provide some insight into conscious motor processes, with more muscular activity characterising explicit consciously controlled movements, and less muscular activity characterising more implicit or autonomous performance.

1.4.3 Electroencephalography

Electroencephalography (EEG) has become one of the most applied neuroimaging approaches to study brain activity (Cheron et al., 2016), because it is non-invasive and relatively cost-effective (compared to other neuroimaging methods) (Thompson, Steffert, Ros, Leach, & Gruzelier, 2008). EEG is a measure of voltage fluctuations in the electrical activity produced by cortical neurons of the brain, which are recorded via electrodes placed on the scalp (e.g., Holmes & Wright, 2017; von Stein & Sarnthein, 2000). Changes in desynchronization and synchronization of patterns of cortical activity generate potentials, which can be measured on the scalp using the EEG electrodes (von Stein & Sarnthein, 2000). EEG has been extensively used to measure cortical activity during movement preparation (see Cooke, 2013, for a review on EEG in sports).

EEG can be analysed in the time-domain or the frequency-domain (see Gross, 2014, for a review), but arguably the most relevant measures for motor performance are derived from the frequency-domain (i.e., EEG spectral power), which will be the focus in this thesis. Spectral power analysis consists of transforming time-based EEG data into frequency-domain signals (Gross, 2014), which are recorded in Hertz (Hz). Hertz refers to the number of cycles or oscillations per second in an EEG waveform (Cooke, 2013; Harmon-Jones & Peterson, 2009). In the broadest sense, spectral power is seen as an indicator of how active neurons are (Klimesch, 1999); however, spectral power in different

frequency bands may reflect different cognitive processes (Janelle et al., 2000; Ray & Cole, 1985), so it is important to identify the frequency band measured to properly interpret spectral power data. For instance, spectral power in the alpha frequency (around 8-12 Hz) might reflect global corticocortical communication, and higher band frequency (e.g., gamma; 35-60Hz) might represent more localized activities (Janelle et al., 2000; Nunez & Cutillo, 1995; Nunez & Srinivasan, 2006). Concerning motor control, theta (4-8 Hz), alpha (8–12 Hz) and beta (13-30 Hz) frequency bands are commonly analysed (Cooke, 2013; Janelle et al., 2000; Klimesch, 1999). However, this thesis will mainly focus on the high-alpha (10-12 Hz) frequency band, because most of the movement specific literature describes findings in this frequency band. Activation of the high-alpha frequency band is thought to be associated with inhibition of nonessential neural processes. Specifically, higher high-alpha power reflects higher inhibition of nonessential processes (e.g., Bellomo, Cooke, & Hardy, 2018; Gallicchio, Cooke, & Ring, 2017; Klimesch, 2012). Additionally, within this thesis the individual alpha frequency peak will be determined for each participant, since studies have revealed that frequency lengths are different for every individual (Corcoran, Alday, Schlesewsky, & Bornkessel-Schlesewsky, 2018).

Since EEG measures are event-locked and analysed in very precise time-windows, it is important to establish the most relevant time window to capture whichever cognitive process is of interest (e.g., verbal-analytical engagement in motor processing, in the case of this thesis). Given that verbal-analytical involvement in movement planning is likely to peak just before movement initiation, most previous EEG and motor performance studies have used a time frame of around 4-7 sec leading up to movement initiation as the duration of interest (e.g., Deeny, Hillman, Janelle, & Hatfield, 2003; Hatfield, Landers, & Ray, 1984; Haufler, Spalding, Santa Maria, & Hatfield, 2000; Hillman, Apparies, Janelle, & Hatfield, 2000; van Duijn, Hoskens, & Masters, 2019). Other studies measure cortical activity just before (i.e., 4 sec) and just after (i.e., 1 sec) movement initiation, to reflect the possibility that some conscious processing could also occur during movement (e.g., Cooke et al., 2015; Cooke et al., 2014; Gallicchio, Cooke, & Ring, 2016). Studies analysing cortical processes in relation to motor performance have mostly used EEG spectral power analyses at individual

electrodes on the scalp to give insight into activation at that location (EEG power), or at pairs of electrodes to assess communication between locations (EEG connectivity or coherence) (see Cooke, 2013, for a review). In this thesis, we applied both analyses. A brief introduction to these analyses is provided below.

1.4.3.1 EEG power

Previous studies have revealed that experts show greater cortical efficiency, compared to novices. Specifically, experts are better able to efficiently control movements by suppressing irrelevant processes (e.g., verbal-analytical processes) in order to perform well (e.g., psychomotor efficiency hypothesis, Hatfield & Hillman, 2001). For example, Haufler et al. (2000) revealed that marksmen showed lower cortical activation compared to novices over the central, temporal and parietal regions during the aiming period of a shooting task. Consequently, studies suggest that experts perform in a more automatized manner (i.e., less cognitive input) than novices, which is mirrored by reduced cortical activity (e.g., Deeny, Haufler, Saffer, & Hatfield, 2009; Gallicchio et al., 2017; Hatfield & Hillman, 2001).

It is commonly believed that the two hemispheres are responsible for different cognitive functions. The left hemisphere is related to verbal-analytical processes, whereas the right hemisphere is related to visual-spatial processes (e.g., Wexler, 1980). Haufler et al. (2000), for example, revealed that alpha power (10-11Hz) over the left regions was significantly higher for experts compared to novices during the 6 sec preceding movement initiation. Alpha power is inversely related to cortical activity, therefore higher alpha power means reduced cortical activity (Hillman et al., 2000; Klimesch, 1999). Consequently, the measure of high-alpha power over the left hemisphere has been associated with the level of verbal (i.e., conscious) information processing when preparing a movement (Cooke, 2013).

The measures of cortical activity (i.e., EEG) have not only been used for skilled performers, researchers have also examined cortical activity during novice motor performance (e.g., Gallicchio et al., 2017; van Duijn et al., 2019; Zhu, Poolton, Wilson, Maxwell, et al., 2011). Van Duijn et al. (2019), for example, revealed that novices practicing a hockey push pass task using an analogy instruction (i.e., implicit motor learning), performed the task with increased high-alpha power in the left-temporal region (T7) during retention, compared to explicit

and discovery (control) motor learning groups. These results provide objective evidence for implicit motor learning to reduce verbal-analytical processing during performance.

1.4.3.2 EEG coherence and connectivity

Two measures have been used by motor performance researchers to assess communication between pairs of electrodes on the scalp. The first and most common is EEG magnitude squared coherence, which is a measure of synchronicity of cortical activity between two electrodes over time (Nunez & Cutillo, 1995; Weiss & Mueller, 2003). The second and more recent measure is Inter Site Phase Clustering (ISPC, Cohen, 2014; Lachaux, Rodriguez, Martinerie, & Varela, 1999), which is referred to as EEG connectivity. The ISPC is computed by the phase angles, which is independent from power differences (Gallicchio et al., 2017). A recent shift towards the EEG connectivity measure has occurred due to concerns that the original magnitude squared coherence measure might be misleading in some experiments due to overall power differences between conditions or groups (EEG connectivity is independent of power) (Cohen, 2014). However, Gallicchio et al. (2017) reported both measures in a golf putting experiment and found that they yielded largely identical effects - thus, both measures are valid. Both measures of synchronicity (coherence and connectivity), have been employed in multiple studies that have sought to determine the cognitive synchronization between different brain regions during motor skill performance (e.g., Babiloni et al., 2011; Deeny et al., 2003; Gallicchio et al., 2016, 2017; Zhu, Poolton, Wilson, Maxwell, et al., 2011).

Most of these studies have examined the level of synchronization between the left temporal (T7) site and the mid-frontal motor planning (Fz) site in the high-alpha frequency (Cooke et al., 2015; Shibasaki & Hallett, 2006). Zhu, Poolton, Wilson, Maxwell, et al. (2011), for example, revealed that during movement preparation participants with a lower propensity to consciously control their movements[7] displayed lower T7-Fz connectivity compared to participants with a higher propensity to consciously control their movements. This highlights T7-Fz

[7] Conscious control was measured by the Movement Specific Reinvestment Scale (Masters & Maxwell, 2008).

synchronization as a potential measure of verbal-analytical engagement in motor planning, with greater T7-Fz synchronisation indicating greater conscious motor control.

There are also studies revealing associations between coherence levels in the temporal and motor planning regions and working memory capacity. For example, van Duijn, Buszard, Hoskens, and Masters (2017) examined high-alpha synchronization between the right temporal (T8) site and the mid-frontal motor planning site (Fz). Results revealed a positive association between T8-Fz coherence and visual-spatial working memory capacity, indicating that performers with high visual-spatial working memory capacity may be more likely to process movement-related information using visuospatial cognitive processes. On the other hand, Buszard et al. (2013) revealed a negative association between T8-F4 coherence and visual-spatial working memory capacity, suggesting that performers with high visual-spatial working memory capacity may be less likely to process movement-related information using visuospatial cognitive process. The seemingly contradictory findings might have been caused by differences in electrode use (i.e., Fz versus F4 electrode), representing different cortical processes. Furthermore, Buszard et al. (2013) revealed a positive correlation between T7-F3 coherence and verbal working memory, implying that a higher verbal working memory capacity is associated with higher verbal-analytical processes during motor performance. In summary, EEG coherence, especially between the T7 and Fz sites, is a strong candidate measure of conscious movement control during motor planning.

1.5 Summary and thesis outline

Implicit motor learning theory suggests that acquisition of a motor skill can occur without conscious involvement (i.e., reduced verbal-analytical processing of movements). Several implicit motor learning paradigms have been developed, such as dual-task learning, analogy learning and error-reduced practice. Significant evidence has accumulated for the benefits of these paradigms, especially under pressure, in demanding contexts (e.g., dual-tasking), or when people are physically fatigued. However, these methods leave room for verbal-analytical engagement in movements, especially by people with high working memory capacity or a high tendency to engage in conscious movement processing. Recent research, therefore,

has suggested that more direct manners of suppressing verbal-analytical engagement during learning and performing complex movements is required.

The aim of this thesis is to test two new potential implicit motor learning paradigms: cognitive fatigue and pre-performance left-hand contraction protocols. Cognitive fatigue has been shown to lower working memory performance on cognitive tasks and invoke procedural learning during a serial reaction time task. However, no research has examined whether cognitive fatigue can be employed to reduce working memory processes involved in a complex motor skill. The pre-performance left-hand contraction protocol has been shown to induce stable performance under pressure, compared with right-hand contractions, possibly because left-hand contractions suppress pressure-sensitive verbal-analytical left hemispheric activity. However, the possibility of causing implicit motor learning by using left-hand contractions to suppress verbal-analytical engagement in motor performance during practice has not yet been examined previously.

The experimental work conducted to achieve the aims of this thesis is presented as a series of studies. Chapters 2 and 3 investigate cognitive fatigue and Chapters 4 and 5 investigate pre-performance left-hand contraction protocols.

The first experiment, reported in Chapter 2, was conducted as a pilot study to examine whether a computer-based cognitive fatigue task could be employed to suppress working memory processes and thus reduce verbal-analytical involvement in a subsequent golf-putting task. Based on previous studies, it was predicted that compared to a non-fatigue control condition the cognitive fatigue task would suppress working memory processes causing reduced verbal-analytical involvement in the motor task. Verbal-analytical involvement was gauged by examining movement adjustments during movement preparation, assessing performance under a dual-task load, and self-report of conscious movement processing.

The second cognitive fatigue experiment, reported in Chapter 3, improved upon the limitations of the first study and replaced the computer-based cognitive fatigue task with a new motor-related cognitive fatigue task, which was designed to place high demands on executive functions involved in motor tasks (i.e., inhibition, updating, switching). First, the new task was validated as a method for causing

cognitive fatigue and then the efficacy of the task was examined during practice of a novel shuffleboard task. It was expected that the task would more effectively suppress executive functions involved in motor tasks and thereby reduce verbal-analytical engagement during subsequent practice of the shuffle-board task. Verbal-analytical engagement was measured objectively using psychophysiological measures and kinematic and solution-driven technique changes, and subjectively via verbal reports.

Chapters 4 and 5 tested whether pre-performance left hand contractions can potential be used to cause implicit motor learning. The third experiment, reported in Chapter 4, examined the effect of hand contractions on motor performance. Based on previous studies, it was predicted that a left-hand contraction protocol would suppress cortical activity in the left hemisphere and therefore lower verbal-analytical engagement in motor planning. Right-hand contractions were expected to increase cortical activity in the left hemisphere and thus raise verbal-analytical engagement in motor planning.

The final experiment, reported in Chapter 5, examined whether left-hand contractions promote implicit motor learning. It was predicted that left-hand contractions prior to practicing a golf-putting task would cause reductions in verbal-analytical processing of movements and promote implicit motor learning. Right-hand contractions were expected to increase verbal-analytical processing of movements during practice, promoting explicit motor learning.

In Chapter 6, key findings are summarised and discussed within the context of current literature. Theoretical and practical implications are evaluated and potential future research directions proposed.

Chapter 2

Experiment 1: The effects of cognitive fatigue on conscious engagement in movement[8]

2.1 Abstract

The aim in this chapter was to investigate whether a computer-based cognitive fatigue task could be used to suppress working memory processes. Compared to a non-fatigued control condition, cognitive fatigue was expected to suppress working memory processes and cause reduced verbal-analytical involvement in a golf putting task. Forty-two right-handed participants who were novices to golf putting were randomly assigned to a cognitively fatigued or non-fatigued (control) treatment. Differences in verbal working memory capacity performance and subjective and objective feelings of cognitive fatigue were examined pre- and post-treatment. Intensity of verbal-analytical engagement during ten golf putting trials (performed immediately post-treatment) was gauged by assessing the number of movement adjustments and self-reports of the amount of conscious motor processing. Finally, a further ten golf putting trials were performed with a concurrent working memory load (secondary task) to determine the influence of the cognitive fatigue manipulation on working memory. Performance of the fatiguing task (TloadDback) did not decrease and verbal working memory (Reading Span Task) was unaffected. However, subjective feelings of fatigue were higher in the cognitively fatigued compared to the non-fatigued (control) group. Neither movement adjustments nor self-reports of the amount of conscious motor processing differed significantly from pre- to post-treatment. Dual-task performance was not different from single-task golf performance in either group. Although the cognitive fatigue manipulation increased subjective levels of fatigue, conscious engagement in moving appeared to be unaffected during golf putting

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[8] Based on: **Hoskens, M. C. J.,** Boaz-Curry, K., Uiga, L., Buszard, T., Capio, C. M., Cooke, A., & Masters, R. S. W. (under review). The effects of cognitive fatigue on conscious engagement in movement, *Human Movement Science*

performance. The fatigue task that we used may not have been sufficiently mentally demanding to reduce conscious motor processing. Future research should test a movement-specific cognitive fatigue task.

2.2 Introduction

Accumulation of task-relevant declarative knowledge occurs when learners search for motor solutions that will improve their performance. Typically, rules or hypotheses are generated and tested, then adjusted if necessary (and sometimes if unnecessary). Eventually, the information is stored as task-relevant declarative knowledge of a motor solution (MacMahon & Masters, 2002; Maxwell et al., 2003). Working memory is thought to be the main cognitive system involved in hypothesis testing (Buszard, Farrow, et al., 2017; Maxwell et al., 2003). Working memory supports processing and manipulation of new information and storage of information in long-term memory (Baddeley, 1992; Bo & Seidler, 2009; Buszard et al., 2013; Just & Carpenter, 1992; Kane & Engle, 2002).

Masters (1992) showed that participants learned more implicitly when they practiced golf putting while carrying out a concurrent secondary task (random letter generation). Masters (1992) argued that the concurrent secondary task used up resources of working memory that were normally available to process hypotheses about possible movement solutions when practicing. Masters (1992) concluded that learners can improve their motor performance without accumulating task-relevant declarative knowledge, which results in implicit motor learning. Implicit motor learning is thought to promote development of more efficient procedural knowledge, with a corresponding reduction in conscious engagement in moving compared to explicit motor learning (e.g., Masters, 1992; Maxwell et al., 2003).

Masters and colleagues have since developed other implicit motor learning paradigms, such as analogy learning (Liao & Masters, 2001) and errorless learning (Maxwell et al., 2001), which aim to reduce working memory involvement during practice. Maxwell et al. (2001), for example, constrained the environment to reduce the amount of errors that occurred during practice, thus reducing the necessity for working memory to be engaged in hypothesis testing because performance was successful. These paradigms, however, influence working memory indirectly, so they do not unconditionally suppress the tendency that people have to use working

memory to process hypotheses (e.g., Buszard et al., 2016). Direct working memory suppression potentially overcomes this issue by blocking access to working memory resources. Zhu et al. (2015), for example, used cathodal (i.e., inhibitory) transcranial direct current stimulation (tDCS) to suppress activity in the left dorsolateral prefrontal cortex (associated with verbal working memory) during practice of a golf putting task. In comparison to sham stimulation (placebo), Zhu et al. (2015) concluded that tDCS of the left dorsolateral prefrontal cortex suppressed verbal working memory activity, thus causing a less explicit, more implicit, mode of learning.

An alternative method by which to cause implicit motor learning may be to exhaust working memory resources needed for hypothesis testing prior to practice. A possible method to achieve this is to induce cognitive fatigue, which is thought to reduce top-down conscious control processes (e.g., Borragan et al., 2016; van der Linden, 2011; van der Linden et al., 2003; Wolfgang & Schmitt, 2009). Wolfgang and Schmitt (2009), for example, found that prolonged performance of a Stroop task (480 trials) caused cognitive fatigue, which disrupted performance. The Stroop task (Stroop, 1935) requires participants to name the colour in which colour words are written (e.g., the word 'green' is written in blue). Successful performance requires participants to consciously inhibit their automatic tendency to read and name the written word. Wolfgang and Schmitt (2009) argued that cognitive fatigue reduced cognitive resources available for top-down conscious inhibition of automatic responses (reading) during Stroop performance.

Borragan et al. (2016) also suggested that cognitive fatigue interferes with conscious control processes. Borragan et al. (2016) examined the effects of cognitive fatigue on learning a serial reaction time task (SRTT). The SRTT requires participants to rapidly press tabs in response to stimuli presented on a screen. Typically, participants are unaware that the order of the stimuli is repeated in a specific sequence, yet they become faster at responding and eventually anticipate accurately the position of each stimulus in the sequence. Borragan et al. (2016) found that cognitive fatigue improved learning of the sequence. They argued that during repetition of the SRTT, cognitive fatigue reduced disruptive top-down conscious interference in the task, which was beneficial for implicit (procedural) learning.

Consequently, top-down processing of task-relevant information needed for hypothesis testing is likely to be suppressed by cognitive fatigue. Should cognitive fatigue interfere with top-down conscious control processes during practice of a motor task (presumably by exhausting working memory), it may thus be possible to cause implicit motor learning. In the present study, we therefore investigated whether cognitive fatigue caused reduced conscious engagement during performance of a motor task. In order to examine this, we asked novice participants to perform a golf-putting task after cognitive fatigue (validated protocol) or after no fatigue (i.e., video watching). We predicted that cognitive fatigue would lower conscious engagement by suppressing working memory activity during the golf putting task.

We used objective and subjective measures to establish whether cognitive fatigue occurred, and asked participants to complete a verbal working memory capacity task to establish the effects on working memory efficiency (Vogel, McCollough, & Machizawa, 2005). Novice participants completed two blocks of golf putting trials in single-task or dual-task conditions immediately following treatment. The dual-task condition was introduced as an additional measure of working memory activity, because secondary tasks are typically thought to consume working memory resources (Masters, 1992; Maxwell et al., 2000, 2003). We therefore expected to see bigger deficits in dual-task relative to single-task performance in the fatigued group compared to the non-fatigued (control) group. Hypothesis testing during the golf putting task was measured objectively by counting the number of movement adjustments (e.g., Maxwell et al., 2003), and subjectively by administering the conscious motor processing (CMP) subscale of the Movement Specific Reinvestment Scale (MSRS, Masters, Eves, & Maxwell, 2005; Masters et al., 1993) as a state measure.

2.3 Method

2.3.1 Participants and Design

Forty-two right-handed novice golfers (mean age = 23.61 years, SD = 5.10 years, 20 female) were recruited to participate in this study. To control for handedness, only right-handed people were included. All participants had normal/corrected vision. The participants were instructed not to consume caffeine 3 hours prior to

testing. A between subjects design was adopted, with participants randomly allocated to a Fatigue group or a Non-fatigue (control) group using a random sequence generator. The study received ethical approval from the University Human Research Ethics Committee.

2.3.2 Treatment

The Time-load Dual-back task (TloadDback, Borragan et al., 2016) was used to cognitively fatigue participants in the fatigued group. The task consisted of a continuous series of numbers and letters displayed on a computer screen in an alternating order. Letters one back in the sequence of letters had to be remembered (traditional N-back task, Kirchner, 1958), and participants were required to press the spacebar on the keyboard when the letter they saw was the same as the previous letter. The digits had to be identified as odd or even, by pressing "1" or "2" on the keyboard (see example in Figure 2.1). Performance during each block was calculated using a letter accuracy by digit accuracy ratio of 6.5:3.5, based on the claim that the one-back task requires more working memory functions than the digit task (Borragan, Slama, Bartolomei, & Peigneux, 2017; Fougnie, 2008).

A similar protocol to Borragan et al. (2017) was employed. Participants first practiced the odd/even task and the one-back task separately, and then together (i.e., TloadDback task), until they understood the task (accuracy levels greater than 85%). Each stimulus was presented on the screen for a stimulus time duration (STD) of 1500 msec. The average total duration of practice was 4 min 58 sec. Following practice, we determined the maximum cognitive load that each participant was able to cope with during the TloadDback task by decreasing the STD from block to block (each block consisted of 60 trials, alternating between odd/even and one-back trials, 30 trials each) until performance level was below 85%. Block 1 used an STD of 1400 msec, which was reduced incrementally by 100 msec on subsequent blocks if performance was successful (i.e., >= 85%). The participant's last successful STD at which accuracy was above 85% was set as the individual maximum cognitive load. The range of blocks completed was between four and seven (mean duration 6 min 33 sec). The TloadDback task was then performed by participants for 16 min to cause cognitive fatigue using their individual maximum cognitive load (TloadDback-fatigue).

The non-fatigue treatment consisted of watching a 25 min nature documentary ('*New Zealand Nature Documentary, Adventure Earth*', YouTube).

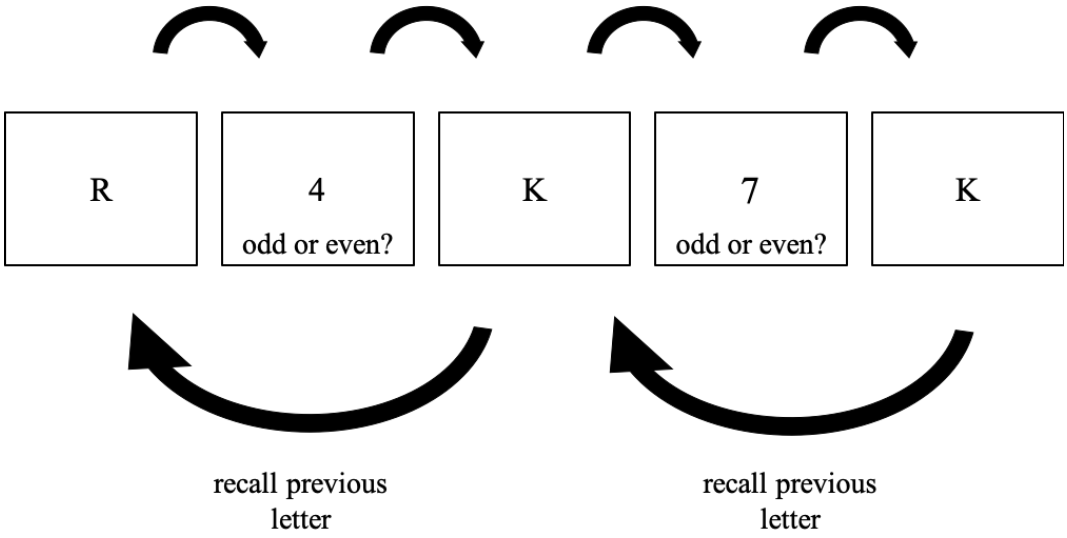

Figure 2.1 Overview of the TloadDback task. This consisted of the traditional one-back task for the letters displayed and a digit decision making task.

2.3.3 Golf putting task

Participants performed golf putts on an artificial grass surface using a standard length golf putter (90 cm) and a regular-size (diameter 4.7 cm) golf ball. The target was a 10.8 cm diameter circle drawn onto the surface of the artificial grass, 3m from the starting position (see Figure 2.2). Putter kinematics were obtained with SAM Puttlab (Science motion GmbH, Munich, Germany, www.scienceandmotion.de) using an overall sample rate of 210Hz (*SAM PuttLab reports manual*, 2010). An inter-trial-interval of 25 sec was used in order to control the duration of each trial. Visual cues on a laptop monitor indicated when participants were to prepare (cue 1) and initiate (cue 2) their movements, with a 6 sec interval between the cues. Thereafter, a 19 sec interval was available for participants to make the putt and the researcher to collect the ball and reposition it in front of the participant. Video cameras filmed each trial for later analysis of the footage.

Figure 2.2 Experimental set-up for the golf putting task.

2.3.4 Measures

2.3.4.1 Manipulation check of cognitive fatigue

An objective measure of cognitive fatigue was obtained by calculating a weighted accuracy measure (%) for TloadDback-fatigue performance during the 16 min (see Borragan et al., 2017; Borragan et al., 2016) of the TloadDback task.

Subjective feelings of fatigue were assessed with an adapted version of the Visual Analogue Scale of Fatigue (VASf, Lee, Hicks, & Nino-Murcia, 1990) (see Appendix 1). The VASf is suggested to be one of the most reliable measures of cognitive fatigue (Smith, Chai, Nguyen, Marcora, & Coutts, 2019). The adapted version contained four questions (out of a total of 18 questions) associated with fatigue and attention (*e.g., 'how tired are you at this moment?'*). Responses ranged on a Likert scale from '*not at all*' (1) to '*extremely*' (10). Total scores ranged between 4 and 40 with higher scores indicative of higher feelings of fatigue.

2.3.4.2 Manipulation checks of working memory suppression

Reading Span Task. The impact of the TloadDback task on verbal working memory capacity performance was determined by administering a computer-based Reading Span Task (Stone & Towse, 2015), designed with *Tatool* software (Training and Testing Tool, von Bastian, Locher, & Ruflin, 2013). During the task, digits and sentences were displayed on a computer monitor in an alternating sequence (see example in Figure 2.3). The STD for digits was 2500 msec and sentences had to be completed as fast as possible. Participants were required to

recall the sequence of the digits at the end of each trial and to judge whether the sentences made sense or not (e.g., '*Christmas is in December'*). The number of digits (and sentences) gradually increased across blocks of trials, with each block consisting of three trials of a similar sequence length.

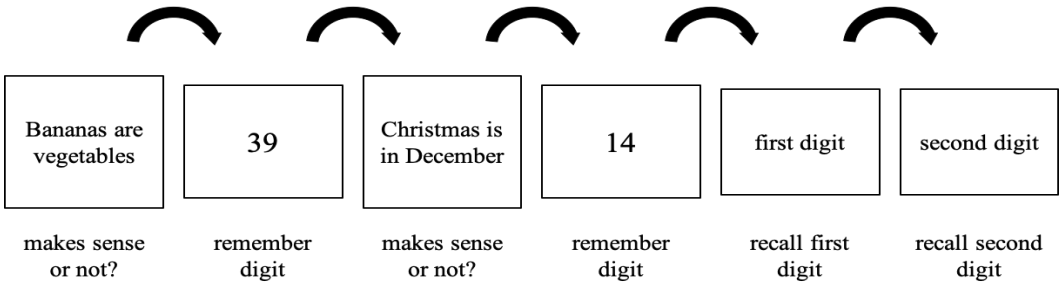

Figure 2.3 Overview of the Reading Span Task. The task requires judging of sentence meanings and recall of digit sequences at the end of each trial.

To ensure that participants focused on both processes, they were required to recall the correct digits in the correct order, and to make at least one correct sentence decision during each trial. Based on the discontinue rule used in the Automated Working Memory Assessment (Alloway, 2007; Alloway, Gathercole, Kirkwood, & Elliott, 2008), the task ended when participants failed all three trials in a block.

During the pre-test, the task started at span-2 difficulty level (i.e., two digits to remember) and incrementally increased in difficulty level until participants failed three trials in a block. The achieved span level was recorded and an immediate re-test was performed, starting one span level higher than the maximum span achieved in the first test. This was done to ensure that participants achieved the highest span level of which they were capable. During the post-test, the task was performed only once (starting at span-2 level) without a re-test, so that it would not dilute cognitive fatigue effects. The total number of correctly remembered digits was scored and used as the Reading Span score for both the pre-test (highest score from test or re-test) and post-test.

Single-task, dual-task performance differences. Differences in golf putting performance and kinematics when participants completed a golf putting task alone (single-task), compared to a golf putting task and a tone-counting task simultaneously (dual-task), were computed to gauge available working memory

resources following the fatigue and non-fatigue (control) treatments (Masters, 1992; Maxwell et al., 2000, 2003).

Golf putting performance was determined by calculating the radial error between the end position of the ball and the target. Kinematics were determined by calculating the standard deviation (SD) of putter velocity at impact (mm/sec) and face angle at impact (degrees) using SAM Puttlab data. These measures have previously been proposed to be important for putting success (Malhotra et al., 2015).

2.3.4.3 Hypothesis testing during motor performance

Subjective level of hypothesis testing was assessed using a modified state-specific version of the Conscious Motor Processing (CMP-state) subscale of the original Movement Specific Reinvestment Scale (MSRS, Masters et al., 2005; Masters et al., 1993). Items were rephrased to reflect how participants felt during the golf putting task. For example, the item of '*I reflect about my movement a lot*' became '*I reflected about my putting movement a lot*'**.** Responses were made on a Likert scale ranging from '*strongly disagree'* (1) to '*strongly agree*' (6). Total scores ranged between 5 and 30 with higher scores indicative of higher conscious motor processing.

Additionally, behavioural measures of hypothesis testing were determined by assessing the number of movement adjustments (fidgets) that participants made during the single-task block of putting trials (Maxwell et al., 2001; Poolton et al., 2005). Adjustments were defined as changes in body positioning, putter movement and motor movements between trials (e.g., placing the feet further apart when lining up for the putt compared to the previous putt). Adjustments were counted by two experimenters who independently examined the video footage of each trial. Intraclass Correlation Coefficients (ICC) revealed moderate reliability between the experimenters, ICC = 0.72, 95% confidence interval = 0.38-0.87, $t(26) = 3.50$, $p = .001$ (Hallgren, 2012).

2.3.4.4 Procedure

Participants were informed about the context of the study and signed an informed consent form before providing general demographics prior to the start of the experiment. A tone counting familiarization task was performed, in which participants were instructed to listen to low (500 Hz) and high (1000 Hz) tones

played by the computer software (Labview Application Builder 2010, National Instruments Inc., Austin, TX) in a randomized order at intervals of 1000 msec. Participants were required to count the number of low tones only. Tones occurred for approximately 30 secs after which participants were asked to report the number of low tones that they heard. Thereafter, two pre-test golf putts were performed[9] and the adapted CMP-state was administered. The pre-test Reading Span Task was conducted, and the VASf was administered before and after the Reading Span Task. Participants then started their treatment (either the TloadDback task or control task). VASf and Reading Span Task were again administered after treatment. Participants then began the golf putting task. One familiarization putt was allowed, followed by ten single-task trials and ten dual-task trials (golf putting plus tone counting as described above). Counterbalancing was not used, because cognitive fatigue was expected to fade over time, which could have influenced the results on the dual-task depending on when it was applied. Finally, participants were asked to complete the adapted CMP-state scale with reference to their single-task putting (see Figure 2.4 for a complete overview of the procedure).

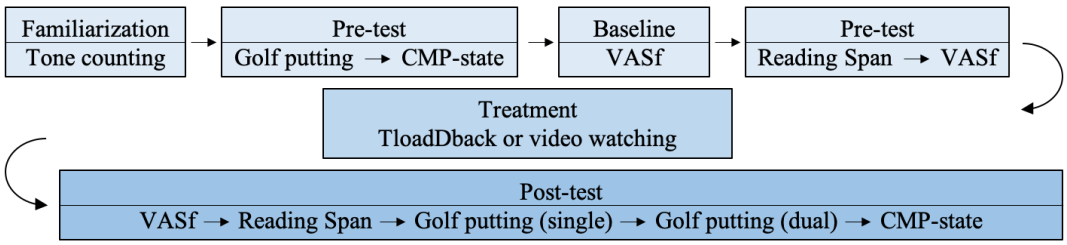

Figure 2.4 Flow diagram of the procedure used for this study.

2.3.5 Statistical approach

The TloadDback-fatigue weighted accuracy measure was divided into four successive time periods (each including around 20% of the total trials) (Borragan et al., 2016) and subjected to a one-way repeated measures (Time period, T1, T2, T3, T4) analysis of variance (ANOVA). A two-way repeated measures ANOVA, Group (Fatigue, Non-fatigue) x Test (Baseline, Pre-, Post-) was used to examine VASf scores.

[9] The pre-test golf putting task consisted of only two trials to minimise the likelihood of participants accumulating declarative knowledge about the task.

Reading Span scores were subjected to a two-way repeated measures ANOVA, Group (Fatigue, Non-fatigue) x Test (Pre-, Post-). Golf putting performance and kinematics were subjected to a two-way repeated measures ANOVA, Group (Fatigue, Non-fatigue) x Task (Single-, Dual-) with pre-test performance (N = 2 trials) included as a covariate. Finally, tone counting accuracy during dual-task putting trials was subjected to a one-way ANOVA of Group (Fatigue, Non-fatigue).[10]

CMP-state scores were examined with a two-way repeated measures ANOVA, Group (Fatigue, Non-fatigue) x Test (Pre-, Post-), and fidgets were subjected to a one-way ANOVA of Group (Fatigue, Non-fatigue).

Sphericity was checked and corrected using the Huynh-Feldt correction when necessary. Separate ANOVAs with Bonferroni corrections were performed when main effects or interactions were found. Effect sizes are reported as partial η squared (η_p^2), with the values .01, .06 and .14 indicating relatively small, medium and large effects sizes, respectively (Cohen, 1988). The statistical tests were performed using SPSS (IBM, version 25.0) computer software. Significance was set at $p = .05$ for all statistical tests.

2.4 Results

2.4.1 Manipulation checks of cognitive fatigue

2.4.1.1 Objective feelings of fatigue

A main effect of Time period was not evident, $F(3,57) = 1.51$, $p = .222$, $\eta_p^2 = .07$ (see Figure 2.5), suggesting that participants were able to maintain performance throughout the TloadDback-fatigue task.

[10] Accuracy on the tone counting task was examined to determine whether participants allocated equal attention to the tone counting task in each group. Typically, accuracy levels greater than 90% are assumed to indicate that participants did not complete one task at the expense of another (e.g., Maxwell et al., 2003).

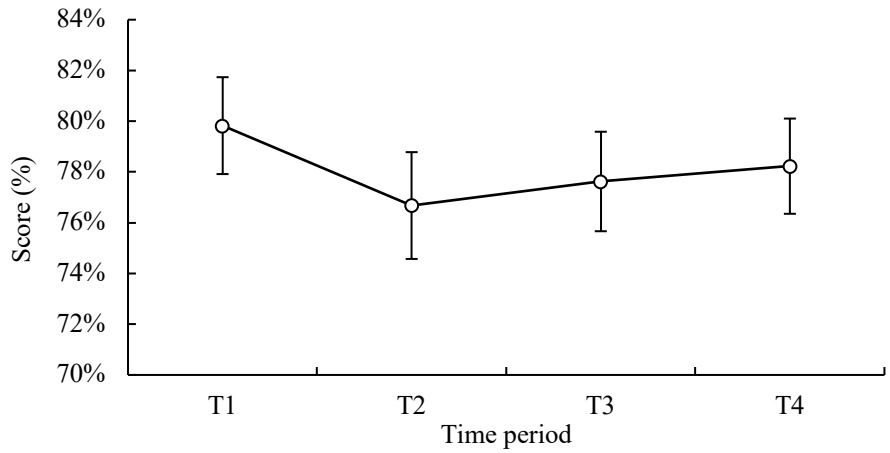

Figure 2.5 Mean TloadDback score in the fatigued group over four time periods. Error bars represent standard error of the mean.

2.4.1.2 Subjective feelings of fatigue

For VASf responses, a main effect of Group was not revealed, $F(1,39) = 3.84$, $p = .057$, $\eta_p^2 = .09$, but a main effect of Test was revealed, $F(2,78) = 47.56$, $p < .01$, $\eta_p^2 = .55$. A Group x Test interaction was also found, $F(2,78) = 12.27$, $p < .001$, $\eta_p^2 = .24$ (see Figure 2.6). Follow-up analysis of variance for each group separately revealed a Test effect in the fatigued group, $F(2,42) = 61.67$, $p < .001$, $\eta_p^2 = .75$, and also in the non-fatigued (control) group, $F(2,36) = 5.26$, $p = .010$, $\eta_p^2 = .23$. Post-hoc analysis revealed that scores in the pre-test and the post-test were significantly higher than at baseline (*p's* < .001) for the fatigued group, and scores at post-test were significantly higher than at pre-test ($p < .001$). For the non-fatigued group, post-hoc analysis revealed that scores in the post-test were significantly higher than at baseline ($p = .017$). Between groups, there were no significant differences in VASf score at baseline, $t(1,39) = 0.96$, $p = .334$, or pre-test, $t(1,39) = 1.07$, $p = .307$; however, at post-test the scores were significantly higher in the cognitively fatigued group than the non-fatigued group, $t(1,39) = 19.20$, $p < .001$.

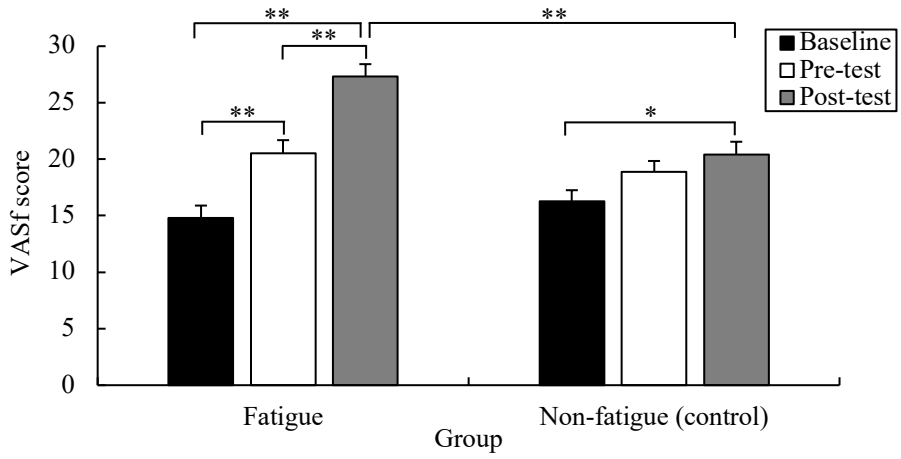

Figure 2.6 Total score on the Visual Analog Scale of fatigue (VASf) for each group at baseline, pre-test and post-test. *$p < .05$, **$p < .001$.

2.4.2 Manipulation checks of working memory suppression

2.4.2.1 Reading Span Task

Mean Reading Span score (i.e., amount of correctly remembered digits) was 54.95 (SD = 23.51) at pre-test and 57.27 (SD = 26.77) at post-test in the fatigued group and 54.75 (SD = 32.51) at pre-test and 47.65 (SD = 25.06) at post-test in the non-fatigued group. Neither a main effect of Group, $F(1,40) = 0.39$, $p = .536$, $\eta_p^2 = .01$, nor a main effect of Test, $F(1,40) = 0.71$ $p = .406$, $\eta_p^2 = .02$, was evident for Reading Span scores. A Group x Test interaction was not present, $F(1,40) = 2.74$, $p = .106$, $\eta_p^2 = .06$.[11]

2.4.2.2 Single-task, dual-task performance differences

Mean Radial Error. Mean radial error was 47.94 cm (SD = 14.68 cm) for single-task and 43.97 cm (SD = 10.43 cm) for dual-task in the fatigue group, and 48.75 cm (SD = 19.32 cm) for single-task and 45.89 cm (SD = 18.31 cm) for dual-task in the non-fatigued group. Neither a main effect of Group, $F(1,37) = 0.09$, $p = .764$, $\eta_p^2 < .01$, nor of Task, $F(1,37) = 0.15$, $p = .706$, $\eta_p^2 < .01$, was found. A Group x Task interaction was not revealed, $F(1,37) = 0.06$, $p = .805$, $\eta_p^2 < .01$.

Kinematics. Mean SD velocity at impact was 173.02 mm/sec (SD = 63.46 mm/sec) for single-task and 130.98 mm/sec (SD = 41.39 mm/sec) for dual-task in the

[11] Given that participants that participants performed the Reading Span task twice at pre-test, we conducted ANCOVA using the average pre-test scores as a covariate. A significant difference was not evident between groups at post-test ($F(1,35) = 0.53$, $p = .471$, $\eta_p^2 = .02$).

fatigued group and 157.50 mm/sec (SD = 68.14 mm/sec) for single-task and 133.75 mm/sec (SD = 55.25 mm/sec) for dual-task in the non-fatigued group. Neither a main effect of Group, $F(1,31) = 0.20$, $p = .659$, $\eta_p^2 = .01$, nor of Task, $F(1,31) = 3.63$, $p = .066$, $\eta_p^2 = .11$ was found, and there was no Group x Task interaction, $F(1,31) = 0.46$, $p = .502$, $\eta_p^2 = .02$.

SD of face angle at impact was 1.62 degrees (SD = 0.88 degrees) for single-task and 1.43 degrees (SD = 0.51 degrees) for dual-task in the fatigued group and 1.35 degrees (SD = 0.81 degrees) for single-task and 1.74 degrees (SD = 0.75 degrees) for dual-task in the non-fatigued group. A main effect of Group was not found, $F(1,31) = 0.01$, $p = .938$, $\eta_p^2 < .01$, but there was a main effect of Task, $F(1,31) = 4.36$, $p = .045$, $\eta_p^2 = .12$, with overall SD of face angle at impact greater during the dual-task group. However, a Group x Task interaction was not revealed, $F(1,31) = 2.57$, $p = .119$, $\eta_p^2 = .08$.

Tone counting. Mean tone counting accuracy was 88% (SD = 15%) for the fatigued group and 90% (SD = 7%) for the non-fatigued group. There was no significant main effect for Group evident, $F(1,39) = 0.36$, $p = .553$, $\eta_p^2 = .01$.

2.4.3 Hypothesis testing during (single-task) motor performance

2.4.3.1 Subjective assessment

Mean CMP-state scores were 24.67 (SD = 3.77) at pre-test and 25.05 (SD = 0.87) at post-test in the fatigued group and 22.95 (SD = 4.33) at pre-test and 24.55 (SD = 0.86) at post-test in the non-fatigued group. Main effects were not found for Group, $F(1,39) = 1.02$, $p = .319$, $\eta_p^2 = .03$, or Test, $F(1,39) = 2.37$, $p = .132$, $\eta_p^2 = .06$, and a Group x Test interaction was not evident, $F(1,39) = 0.90$, $p = .349$, $\eta_p^2 = .02$.

2.4.3.2 Objective assessment

Mean number of movement adjustments were 3.34 (SD = 0.72) and 2.94 (SD = 1.99) in the fatigued and non-fatigued groups, respectively. The mean scores were not significantly different, $F(1,37) = 0.34$, $p = .561$, $\eta_p^2 = .01$.

2.5 Discussion

Our results show no objective evidence of cognitive fatigue, since performance of the TloadDback-fatigue task did not decrease over time. These results contradict the findings of Borragan et al. (2016) and Borragan et al. (2017); however, they are

in line with Borragan, Guerrero-Mosquera, Guillaume, Slama, and Peigneux (2019), who also found that performance did not decrease during the TloadDback-fatigue task. Borragan et al. (2019) argued that participants dedicated more cognitive effort to maintaining performance as they fatigued, which may also explain why our participants did not display reduced performance during the TloadDback-fatigue task. However, while the average maximum cognitive load (i.e., last successful STD at which accuracy was above 85%) of our participants was similar to participants in the Borragan et al. (2017) study, our participants did not perform at their maximum cognitive load (i.e., accuracy was below 85%) during the TloadDback-fatigue task, which may explain why their performance did not appear to decrease. Borragan et al. (2017) and Borragan et al. (2016) completed their TloadDback practice and maximum cognitive load protocol on the day preceding the TloadDback-fatigue task, whereas we completed the whole experiment in a single day. It is, therefore, possible that our participants were bored or less motivated to perform at their maximum cognitive load during the TloadDback-fatigue task than participants in the Borragan et al. (2017) and Borragan et al. (2016) studies.

Similarly to Borragan et al. (2016), participants in the fatigued group self-reported higher feelings of mental fatigue following the TloadDback task compared to baseline, and compared to the non-fatigued group. However, participants in the non-fatigued group also reported significantly greater feelings of fatigue compared to baseline, which may have occurred because of boredom when watching the documentary. Other studies have also shown that boredom can lead to cognitive fatigue (e.g., Smith et al., 2019; Tanaka et al., 2012; Tanaka, Mizuno, Tajima, Sasabe, & Watanabe, 2009).

Contrary to our predictions, the fatigue treatment did not affect performance of the Reading Span Task, suggesting that verbal working memory was not suppressed after performing the TloadDback task. This is perhaps not surprising given that the objective measure of fatigue did not reveal that participants were fatigued. It is also possible that the Reading Span Task that we used was not challenging enough to reveal an effect of cognitive fatigue on working memory processes. Van der Linden et al. (2003) suggested that simple memory tasks (i.e., Digit Span Task) are not affected by cognitive fatigue. They suggested that

cognitive fatigue influences mainly information processing and manipulation, rather than just the ability to temporarily hold information in working memory. Even though the Reading Span Task that we used required judgment of sentences, it did not require manipulation of information.

Additionally, golf putting performance was not disrupted in dual-task relative to single-task conditions, suggesting that working memory processes were unaffected by the fatigue manipulation. It should be noted that the participants in the present study were all novices with highly variable performance (e.g., Deeny et al., 2009; Gray, 2011), so it is possible that potential effects of cognitive fatigue were camouflaged.

Last, neither the subjective nor behavioural measures of hypothesis testing about the motor task (i.e., self-report and fidgets) were significantly different between groups. Relatively high scores on the adapted CMP-state scale were reported in both groups,[12] which suggests that participants were consciously engaged in the putting task and potentially testing hypotheses. High levels of hypothesis testing are common among novices as they search for motor strategies that will correct errors (e.g., Baumeister, Reinecke, Liesen, et al., 2008; Fitts & Posner, 1967).

These findings imply that the TloadDback task caused participants to feel cognitively fatigued without causing noticeable differences in their working memory abilities or in the extent to which they consciously engaged in the golf putting task.

There are several implications from this study, which can be used in future studies to more precisely investigate the association between cognitive fatigue and conscious engagement in movements. It is likely that the TloadDback task influences performance of simple motor tasks (e.g., Borragan et al., 2016) to a greater extent than more complex motor tasks such as those required in sports. The serial reaction time task specifically involves processes of '*where*' to move, but complex motor tasks, such as those in sport, also involve processes of '*how*' to move, which is likely to motivate more hypothesis testing (e.g., Raab, Masters, &

[12] Both groups scored around 25 out of 30 on the CMP-state.

Maxwell, 2005). Additionally, complex motor tasks rely on different brain regions compared to simple motor tasks (e.g., Hardwick, Rottschy, Miall, & Eickhoff, 2013), which may be more susceptible to cognitive fatigue. We therefore suggest that future cognitive fatigue tasks should be designed specifically to affect working memory processes involved in complex motor skill acquisition (i.e., '*how'* to move). For example, the executive functions of working memory (i.e., inhibition, switching and updating of information; Miyake, 200) are highly relevant for hypothesis testing during complex motor skills (Baumeister, Reinecke, Liesen, et al., 2008; Baumeister, Reinecke, & Weiss, 2008; Diamond, 2000; Yogev-Seligmann et al., 2008). Furthermore, measures of neural activity may reveal useful additional information about the effects of cognitive fatigue on working memory processes (e.g., Barwick, Arnett, & Slobounov, 2012; Boksem et al., 2005; Boksem, Meijman, & Lorist, 2006; Borghini, Astolfi, Vecchiato, Mattia, & Babiloni, 2012; Lorist et al., 2009; Lorist, Boksem, & Ridderinkhof, 2005). For example, after performance of a cognitively demanding task for 90 min, Barwick et al. (2012) not only found that participants performed worse on a Stroop task compared to pre-test, but also that altered neural activity manifested as increased alpha power in the anterior (left parietal and pre-central) brain regions, during the Stroop task performance. Barwick et al. (2012) concluded that cognitive fatigue had caused reduced neural activity in the anterior brain region. Interestingly, Hatfield and Hillman (2001) have proposed a psychomotor efficiency theory of neural activity during motor performance, which suggests that increased alpha power (i.e., reduced neural activity) is associated with more automated, efficient performance. Taken together, these reports provide promising evidence that prolonged fatiguing of specific working memory functions (e.g., inhibition) could induce a brain state conducive to implicit motor learning. Therefore, our original theorising that fatigue could facilitate implicit motor learning still warrants further research.

To conclude, participants reported increased feelings of cognitive fatigue following the prolonged TloadDback task, but this was not matched by objective levels of cognitive fatigue. Consequently, we saw no suppression of working memory activity or evidence of reduced hypothesis testing during motor performance. Before we can investigate whether cognitive fatigue has potential to promote implicit motor learning, we first must develop a more effective method for

causing cognitive fatigue in complex motor tasks, such as those used in sports. We suggest that future studies should utilize a cognitive fatigue manipulation that focuses specifically on working memory functions (e.g., inhibition, shifting and updating), in order to more directly influence conscious engagement in movement execution.

Chapter 3

Experiment 2: The effects of fatigued working memory functions on hypothesis testing during acquisition of a motor skill[13]

3.1 Abstract

The computer-based cognitive fatigue task conducted in Experiment 1 caused increased subjective feelings of fatigue, but did not disrupt working memory sufficiently to suppress reduce verbal-analytical engagement during motor performance. It was concluded that the computer-based cognitive fatigue task did not specifically target working memory processes related to motor control. Experiment 2, therefore, improves upon the limitations of Experiment 1 by testing a cognitive fatigue task that was designed to place more demands on executive functions (inhibition, switching, updating) involved in motor tasks. Fifty-nine participants were randomly assigned to a cognitively fatigued or non-fatigued (control) group. The cognitively fatigued group completed a cognitively demanding motor task, whereas the control group completed a non-cognitively demanding motor task. Feelings of fatigue, working memory functions, Fz theta power and vagal control were assessed pre- and post-task to quantify working memory activity. Thereafter, three blocks of 20 trials of an adapted shuffleboard task were completed to determine the impact on hypothesis testing. Hypothesis testing was assessed by self-report, video analysis of technique changes and equipment-use solutions. Additionally, verbal-analytical engagement in motor performance was (indirectly) gauged by computing electroencephalography (EEG) measures of activity over the verbal-analytical (T7) and motor planning (Fz) regions of the brain. The cognitive fatigue task resulted in greater feelings of fatigue, and moderated working memory

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[13] Based on: **Hoskens, M. C. J.,** Uiga, L., Cooke, A., Capio, C. M., & Masters, R. S. W. (under review). The effects of fatigued working memory functions on hypothesis testing during acquisition of a motor skill, *Journal of Experimental Psychology: General.*

functions and Fz theta power compared to the non-fatigue control task. During practice of the adapted shuffleboard task, participants in the fatigued group displayed more technique changes and higher verbal-analytical engagement in motor planning (EEG measures) compared to the non-fatigued control group. No between-group differences were evident for performance accuracy, equipment-use solutions or self-reports of hypothesis testing. The cognitive fatigue task suppressed working memory functions, but resulted in more rather than less hypothesis testing during practice of the shuffleboard task. The implications are discussed in the context of implicit motor learning theory.

3.2 General introduction

It has been claimed that working memory supports the processing, storage and manipulation of information (Baddeley, 1992; Bo & Seidler, 2009; Just & Carpenter, 1992; Kane & Engle, 2002) and underpins explicit motor learning by supporting the development and storage of rules and information about how a motor task is performed (e.g., MacMahon & Masters, 2002; Maxwell et al., 2003).

Limiting the role of working memory in practice has been shown to lead to development and storage of much less information, in a process described as implicit motor learning (Masters, 1992). Masters (1992) demonstrated that participants learned a golf putting skill more implicitly when they practiced while carrying out a concurrent secondary task. The task, random letter generation, was designed to use resources of working memory normally used to process hypotheses about movement solutions. Masters (1992) concluded that motor performance can improve without the accumulation of rules and information about how to perform. Consequently, Masters (1992) argued that this type of learning, implicit motor learning, promotes reduced conscious engagement in performance compared to explicit motor learning (e.g., Masters, 1992; Maxwell et al., 2003).

Masters and colleagues have since developed other implicit motor learning paradigms, such as analogy learning (Liao & Masters, 2001) and error-reduced learning (Maxwell et al., 2001), which aim to reduce working memory activity during practice. Maxwell et al. (2001), for example, constrained the environment to reduce the amount of errors that occurred during practice, thus reducing the necessity for working memory to be engaged in hypothesis testing because

performance was successful. These paradigms, however, influence working memory indirectly, so they do not unconditionally suppress the tendency that people have to use working memory to process hypotheses (e.g., Buszard et al., 2016). Direct working memory suppression potentially overcomes this issue by blocking access to working memory resources. Zhu et al. (2015), for example, used cathodal (i.e., inhibitory) transcranial direct current stimulation (tDCS) to suppress activity in the left dorsolateral prefrontal cortex (associated with verbal working memory) during practice of a golf putting task. Zhu et al. (2015) concluded that in comparison to sham stimulation (placebo), tDCS of the left dorsolateral prefrontal cortex suppressed verbal working memory activity, thus causing a less explicit, more implicit, mode of learning.

Cognitive fatigue potentially is also a method by which to suppress verbal working memory activity. Cognitive fatigue has been shown to reduce top-down conscious control processes (e.g., Borragan et al., 2016; van der Linden, 2011; van der Linden et al., 2003; Wolfgang & Schmitt, 2009). Borragan et al. (2016), for instance, examined the effects of cognitive fatigue on learning a serial reaction time task (SRTT). The SRTT requires participants to rapidly press buttons indicating the location of stimuli presented on a screen. Typically, participants are unaware that the order of the stimuli is repeated in a specific sequence, yet they become faster at responding and eventually anticipate accurately the position of each stimulus in the sequence. Borragan et al. (2016) found that cognitive fatigue improved learning of the sequence. They argued that during repetition of the SRTT, cognitive fatigue inhibited disruptive top-down conscious interference in the task, which was beneficial for implicit (procedural) learning. Consequently, we argued in Chapter 2 that prior to motor performance (or practice), fatiguing working memory resources needed for conscious verbal-analytical processes, such as hypothesis testing, potentially is another method by which to cause implicit motor learning.

Based on these findings, we hypothesised in Chapter 2 that processing of task-relevant information needed for hypothesis testing is likely to be reduced if cognitive fatigue is used to suppress working memory activity prior to motor practice. As a consequence, less information should be stored about motor performance, resulting in implicit motor learning. We adopted the Borragan et al. (2016) task in Chapter 2 to fatigue participants prior to performing a golf putting

task, but despite higher subjective feelings of cognitive fatigue participants did not display suppressed working memory activity (or reduced hypothesis testing) during performance of the putting task. We concluded in Chapter 2 that the Borragan et al. (2016) task may be appropriate for simple motor tasks, which rely primarily on '*where*' to move, but not complex motor tasks, which rely on processes of '*how*' and '*where*' to move. We argued in Chapter 2 that for complex tasks, such as those in sport, the process of solving '*how'* to move is likely to dramatically increase motivation to test hypotheses. Hence, the cognitive fatigue task developed by Borragan et al. (2016) may not have been strong enough to override motivation to test hypotheses.

Consequently, we developed a new cognitive fatigue task to better disrupt or reduce verbal-analytical engagement (and thus hypothesis testing) in more complex, goal driven sports tasks. We incorporated two important modifications. First, we designed a cognitive fatigue task with greater emphasis on motor control. Second, we focused on working memory efficiency (i.e., information processing), rather than working memory capacity. The executive functions of working memory are thought to play a major role in information processing by *updating* old information with new information, *switching* between incoming information, and *inhibiting* irrelevant incoming information (Karatekin et al., 2000; Miyake et al., 2000). These processes are also predicted to play an important role in motor performance (Baumeister, Reinecke, Liesen, et al., 2008; Diamond, 2000; Yogev-Seligmann et al., 2008). Therefore, our cognitive fatigue task required inhibition, switching and updating in order to catch different coloured balls in a particular sequence. Additionally, we added neural measurement to gather biological evidence of the effects of cognitive fatigue on working memory efficiency and verbal-analytical engagement in motor performance. Finally, the motor task that participants practiced when they were cognitively fatigued was designed so that we could objectively assess hypothesis testing. The experiment was conducted in two stages (Experiment 2a & 2b). First, we investigated whether working memory suppression was caused by our cognitive fatigue task and second, we asked whether this caused reduced verbal-analytical engagement and hypothesis testing when practicing a complex motor skill, compared to a non-fatigued (control) group (see Figure 3.1).

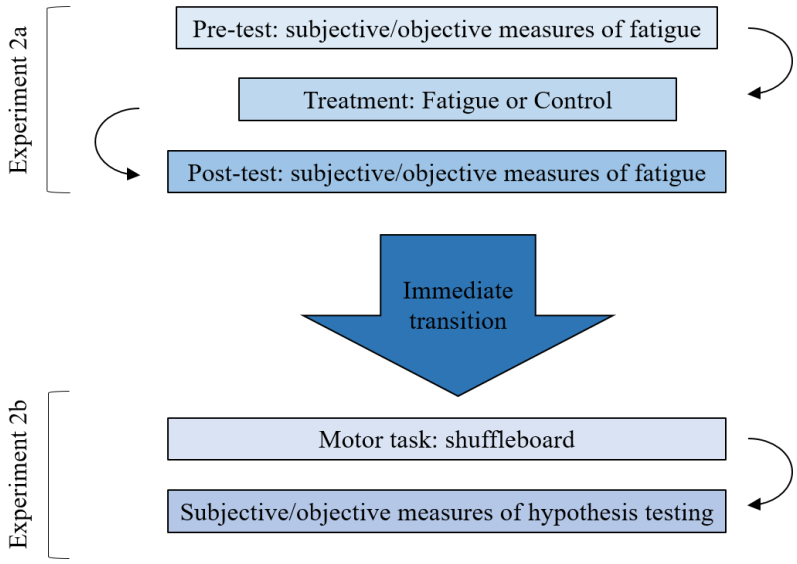


Figure 3.1 Flow diagram of the procedure used for this study.

3.3 Experiment 2a

In the first stage of the experiment, subjective feelings of fatigue and mental effort were assessed to determine how demanding the newly designed cognitive fatigue task was. Additionally, we measured the effect of the task on the performance of computer-based tasks designed specifically to assess executive functions (inhibition, switching, and updating). Theta (4-7 Hz) power at the frontal midline (i.e., Fz region) of the brain was also measured during performance of the executive function tasks, using electroencephalography (EEG), in order to gauge the effect of cognitive fatigue on working memory activity. The frontal midline Fz site overlies the prefrontal cortex, where working memory activity is thought to occur (e.g., Imburgio & Orr, 2018; Jensen & Tesche, 2002; Klimesch, 1999; Miller & Cohen, 2001), and theta power in the Fz region (Fz theta power) is associated with working memory functions, including information maintenance and processing (Jensen & Tesche, 2002; Sauseng, Griesmayr, Freunberger, & Klimesch, 2010). Research has shown that Fz theta power increases in response to cognitive fatigue, suggesting that working memory functions are impacted negatively (Boksem et al., 2005; e.g., Kato et al., 2009; e.g., Wascher et al., 2014). Wascher et al. (2014), for example, revealed that theta power increased as participants became mentally fatigued during a Simon effect task (4 hours). The Simon effect task is a cognitively demanding

spatial stimulus-response compatibility task, which therefore impacts working memory.

We also measured cardiac vagal control during performance of the executive function tasks by assessing heart rate variability (HRV), which is the variability in time between heartbeats (Laborde, Mosley, & Mertgen, 2018). The '*neurovisceral integration model'* (Thayer, Hansen, Saus-Rose, & Johnsen, 2009) suggests that there is a connection between the prefrontal cortex and the heart through the central autonomic network and the vagus nerve. Specifically, this model suggests that reduced prefrontal cortex activity leads to decreased cardiac vagal control. Consequently, HRV may be an indirect measure of working memory efficiency because of the association between the prefrontal cortex and working memory (Hansen, Johnsen, & Thayer, 2003; Laborde, Furley, & Schempp, 2015; Thayer et al., 2009). Hence, if cognitive fatigue suppresses working memory functions, this should be reflected by reduced cardiac vagal control (i.e., HRV) (Tanaka et al., 2009).

We hypothesized that the cognitive fatigue task would require considerable effort and would thus cause high perceived feelings of mental fatigue compared to a non-fatigued control group. We also expected to see decreased performance of the executive function tasks. Furthermore, in this study we predicted that cognitive fatigue would increase Fz theta power and reduce HRV during the executive function tasks compared to no cognitive fatigue.

3.4 Method

3.4.1 Participants and Design

Fifty-nine people were recruited to participate in the experiment (mean age = 24.08 years, SD = 5.74 years, 35 female). To control for handedness,[14] only right-handed people were included. All participants had normal/corrected vision. The participants were instructed not to consume alcohol or drugs 24 hours prior to testing or caffeine 3 hours prior to testing, and to obtain at least 6 hours of sleep the night before testing. A small incentive (10NZD) was provided for participating. A between subjects design was adopted, with participants randomly assigned to a

[14] Only right-handed participants were included, because hemisphere dominance is potentially influenced by handedness (e.g., Grabowska et al., 2012).

Fatigue group [15] or a Non-fatigue (control) group using a random sequence generator. The study received ethical approval from the University Human Research Ethics Committee.

3.4.2 Treatment Task

Participants were required to complete a ball catching task on a standard table tennis table (276 x 153 x 76 cm), during which table tennis balls were projected down the centre line with a table tennis ball machine (Robo-Pong 2040, Newgy industries) starting with a frequency of approximately 23 balls/min. The balls were coloured (white, blue, black and orange) and were mixed regularly in the tray to ensure the colours were randomly dispersed. Participants were instructed to catch the balls with both hands and to place them in a container standing immediately in front of them.

3.4.2.1 Fatigue group

The task was performed over five levels (approximately 3 min each), which increased incrementally in difficulty. The cognitive fatigue task was designed to target the executive functions of working memory, with the following instructions:

"*The ball machine will be shooting different coloured balls to you; you are required to catch the balls with both hands and to put them in the container in front of you. But, there is always one colour that you are not catching, you just let this ball go* [inhibition]. *During the task, I* [i.e., researcher] *will tell you which colour you are not catching* [switching]. *Each time you catch a ball call out loud the colour of the previous ball that came out of the machine* [1-back, updating]. *In between levels, I* [i.e., researcher] *will give you a starting number, and you have to count backwards in sevens from that number."*

The colour of the ball that was not to be caught switched after every ten trials during the first level of the fatigue task. During the second level, this decreased to every six trials, after which it decreased by one during each subsequent level. The number of colours also changed between levels. During the first level, the colour of the ball that was not to be caught switched between black and blue,

[15] Two participants were excluded from analysis because they were unaffected by the fatigue intervention (i.e., unfatigued).

but during the second level, the colour not to be caught switched between black, blue, and orange. During the third level, the colour of the ball not to be caught switched between blue, orange and white, whereas during the fourth and fifth levels, the colour not to be caught switched between all four colours (black, blue, orange, and white). To maintain fatigue, participants were required to count backwards in sevens between levels while the researcher replaced the balls in the ball machine (30 sec).

3.4.2.2 Non-fatigue (control) group

Participants were required to audibly identify the colour of the ball that was caught (0-back). Ball frequency was increased incrementally from approximately 23 balls/min to 37 balls/min across levels to maintain engagement in the task**.** Participants rested between levels (30 sec).

3.4.3 Measures – manipulation checks

3.4.3.1 Feelings of fatigue and mental effort

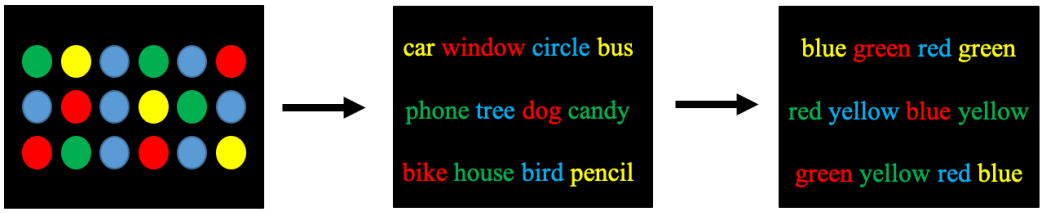
Subjective feelings of fatigue were measured with an adapted version of the Visual Analogue Scale of Fatigue (VASf, Lee et al., 1990) (see Appendix 1). The scale consists of four questions related to fatigue and attention (*e.g., 'how tired are you at this moment?'*). Each question is rated using a Likert scale ranging from '*not at all*' (1) to '*extremely*' (10). The National Aeronautics and Space Administration-Task Load Index (NASA-TLX) was used to measure the amount of mental effort participants utilised while performing the fatigue and non-fatigue (control) task (Hart & Staveland, 1988; Mueller & Piper, 2014). This scale consists of six questions related to mental effort (e.g., '*how hurried or rushed was the pace of the task?').* Responses were marked on a vertical line ranging from '*very low*' (1) to '*very high'* (21). Both scales were presented via *Psychology Experiment Building Language* (PEBL, Mueller & Piper, 2014) and the average was computed for each scale.

3.4.3.2 Computer-based executive function tasks

Three different computer-based executive function tasks were presented via PEBL (Mueller & Piper, 2014). Randomization of task stimuli was performed between

and within participants by the PEBL software. The average duration of each task was 1 min and 40 sec.

Inhibition. The Victoria Stroop task (Troyer, Leach, & Strauss, 2006), which is a brief version of the Stroop task (Stroop, 1935), was used to assess the ability to inhibit irrelevant stimuli. The Victoria Stroop task has been shown to have a high test-retest reliability (Troyer et al., 2006). The Victoria Stroop task includes three blocks of twenty-four trials. Block 1, the *dot* block, displayed dots in different colours (see Figure 3.2). Block 2, the *word* block, displayed random words in different colours (e.g., car, see Figure 3.2). Block 3, the *interference* block, displayed names of colours written in a different colour (e.g., yellow written in green letters, see Figure 3.2). Block 1 and 2 were used for familiarization, whereas Block 3 tested inhibition. Participants were required to indicate the colour of the dot or word by pressing the key representing either red, blue, green or yellow. Trials were repeated if an answer was incorrect.



dot block *word* block *interference* block

Figure 3.2 Overview of the Victoria Stroop task. The dot, word and interference blocks are shown from left to right.

Switching. The Plus-Minus task was used to assess the ability to switch between task requirements (Jersild, 1927; Miyake et al., 2000; Spector & Biederman, 1976). To our knowledge, test-retest has not be reported for the Plus-Minus task. The task consisted of three blocks of ten trials. Block 1, the *addition* block required participants to add 3 to each number that was displayed, by typing it on the keyboard (see Figure 3.3). The next number was then displayed. Block 2, the *subtraction* block, required participants to subtract 3 from each number, and Block 3, the *switching* block, required participants to alternate between adding and subtracting 3 from the displayed number (see Figure 3.3).

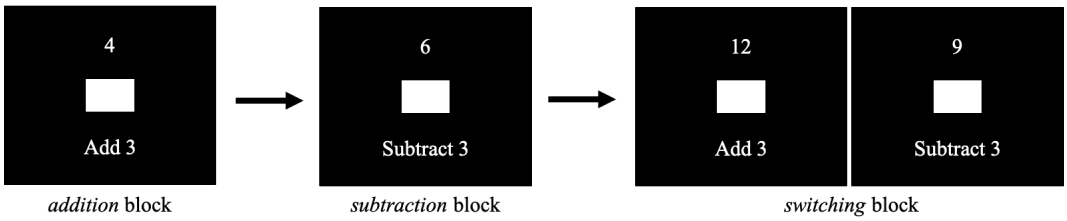


Figure 3.3 Overview of the Plus-Minus task. The addition, subtraction and switching block are shown from left to right.

Updating. The N-back task was used to assess updating abilities (Kirchner, 1958; Oberauer, 2005; Salthouse, Atkinson, & Berish, 2003). The N-back task has adequate test-retest reliability (Soveri et al., 2018). The task consisted of three blocks. For each block a sequence of letters was displayed, with an inter-stimulus interval of 3000 msec. Block 1 required participants to remember the letter displayed one-back in the sequence, and press the shift on the keyboard when the letter they saw was the same as the previous letter. Eleven letters were presented sequentially with the same letter presented in the sequence on four random occasions. Block 2 required participants to recall the letter displayed two back in the sequence and to press the shift key when the letter two back was the same (see Figure 3.4 for example of 2-back updating). Twelve letters were presented sequentially with the same letter presented two back in the sequence on four random occasions. Block 1 and Block 2 were practice blocks, whereas Block 3 was a test block. Block 3 required participants to recall the letter displayed two back in the sequence and to press the shift key when the letter two back was the same. However, twenty-two letters were presented sequentially with the same letter presented two back in the sequence on six random occasions.

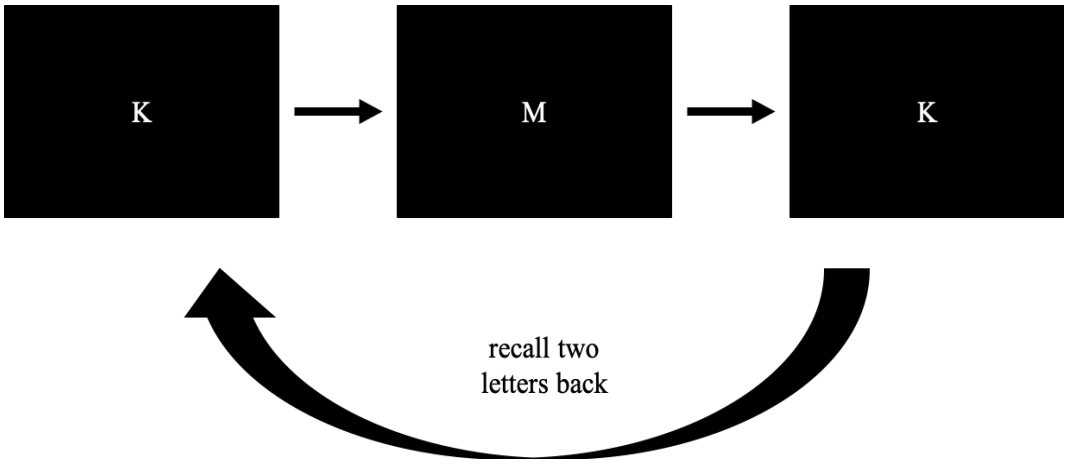


Figure 3.4 Overview of the 2-back task. An example of a letter sequence is shown, with the letter 'K' representing the 2-back rule.

3.4.3.3 EEG power

EEG was used to assess cortical activity during the computer-based executive function tasks. EEG was recorded from eight active electrodes, six of which were positioned over specific regions of the brain, using the 10-20 system (Jaspers, 1958): T7, T8, Fz, F3, FP1, Cz. Additionally, two electrodes were placed on the right and left mastoids (Neuroprene 8-electrode cap, Neuroelectrics, Barcelona, Spain). Common Mode Sense (CMS) and Driven Right Leg (DRL) electrodes were used to increase the common mode rejection ratio of the EEG signals. EEG signals were amplified and digitized at 1024 Hz, with 24-bit resolution (Neurosurfer, Neuroelectrics, Barcelona, Spain).

3.4.3.4 Cardiac vagal control

Cardiac vagal control during the executive function tasks was obtained by measuring heart rate (HR) activity (beats per minute, BPM), from which HRV was extrapolated. A RS800CX Polar HR monitor system was used (Polar Electro, Kempele, Finland). The system has previously been validated for measuring HR activity (Weippert et al., 2010). The signal (received from a chest strap) was stored in Polar ProTrainer 5^{tm} software and offline cleaned and analysed with Kubios software (standard version, 3.3, Biosignal, Analysis and Medical Imaging Group, University of Kuopio, Finland, developed in Matlab 2012a; Tarvainen, Niskanen, Lipponen, Ranta-Aho, & Karjalainen, 2014).

3.4.4 Procedure

Participants were informed about the context of the study and signed an informed consent form before providing general demographics prior to the start of the experiment. An EEG cap and HR monitor band were fitted and a 4 min EEG and HR resting state assessment was performed (2 min with closed eyes and 2 min with open eyes). Detailed instructions about each task in the experiment were provided in order to minimize explanation time between tasks. Participants completed the VASf scale and the three computer-based executive function tasks (Victoria Stroop, Plus-Minus, and N-back) pre-fatigue and post-fatigue (or control). The NASA-TLX was completed post-fatigue (or control) task. The task (fatigue or non-fatigue) was performed at five levels (total duration around 15 min). Participants were informed that it was important to complete all five levels in order to proceed to the next stage of the experiment (i.e., Experiment 2b) to assure engagement of the participants.

3.4.5 Data analyses

3.4.5.1 Computer-based executive function tasks

Inhibition. Performance was determined by the amount of responses made to successfully complete the Victoria Stroop task (score) and task duration for each of the three task conditions (*dot, word, interference*).[16] The inhibition-cost for the *interference* block was computed by relating the amount of trials (inhibiton-$cost_{score}$) and duration time (inhibiton-$cost_{duration}$) of the *interference* block with the *dot* block and the *word* block:

$$\text{Inhibition-cost} = \textit{interference}\ \text{block} - \frac{(\textit{dot}\ \text{block} * \textit{word}\ \text{block})}{(\textit{dot}\ \text{block} + \textit{word}\ \text{block})}$$

The inhibition costs were computed to control for any gross psychomotor speed (Strickland, D'Elia, James, & Stein, 1997). A higher score indicates worse performance on the interference block (Strickland et al., 1997).

Switching. Performance was determined by the number of correct answers (i.e., score), completion time and median reaction time (RT) for the three different blocks

[16] Non-native English speakers (N = 8) were excluded from this analysis because their performance on an English version Stroop task may not have accurately represented their inhibition ability (Rosselli et al., 2002).

in the Plus-Minus task.[17] The switching-costs were computed by relating the score of the *switching* block with the average of the *adding* and *subtracting* blocks, separately for number of correct answers (switching-cost$_{score}$), RT (switching-cost$_{RT}$) and completion time (switching-cost$_{duration}$) (Miyake et al., 2000):

$$\text{Switching-cost} = \textit{switching}\ \text{block} - \frac{\textit{addition}\ \text{block} + \textit{subtraction}\ \text{block}}{2}$$

The switching-costs were computed to control for any overall difficulties with mathematical performance (Miyake et al., 2000). However, the switching-cost$_{score}$ entails an opposite interpretation from the switching-cost$_{duration}$ and switching-cost$_{RT}$. A higher switching-cost$_{score}$ means more correct answers for the switching block compared to the other two blocks (addition and subtraction), whereas higher switching-cost$_{duration}$ and switching-cost$_{RT}$, means longer response time for the switching block compared to the other two blocks.

Updating. Performance was determined by calculating the number of correct responses,[18] together with RT on the correct target letter trials (i.e., when response is required) on the N-back task.

3.4.5.2 EEG power

EEG signals captured during performance of the executive function tests were processed offline using EEGlab software (version 14, Delorme & Makeig, 2004), running on Matlab software (MathWorks, Inc., USA version 2018b). The data was resampled to 250 Hz and band pass filtered (1-35Hz band pass filter), re-referenced to the average of the two mastoids and de-trended. Baseline correction was completed and electromyography (EMG) and electrooculography (EOG) artefacts were removed using Blind Source Separation (AAR plug in; Gomez-Herrero et al., 2006), and Least Mean Squares regression (Gomez-Herrero et al., 2006; Haykin, 1996). The signals were epoched and then subjected to a threshold-based artefact removal procedure, where any 250 msec window containing signal fluctuations exceeding ±75 μV was rejected.

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[17] Participants unable to achieve more than five correct answers in either addition or subtraction block during the pre-test were excluded (N = 1).

[18] The score was taken from all trials, including the correct response to non-target letters (not responding) and target letters (responding). This was done, because otherwise, performance would only be computed from six trials.

The clean signal was subjected to time frequency analysis to obtain the estimated instantaneous theta power for 28 sec (the maximum duration after artefact removal) of each of the three executive function tasks. This analysis was performed by convolving the fast Fourier transform (FFT) power spectrum of the signal with a family of complex Morlet wavelets and eventually taking the inverse FFT (Cohen, 2014). Power at each frequency bin was defined as the squared magnitude of the results of the convolution and averaged across the theta (4-7 Hz) frequency band. To ensure normal distribution, all power estimates were subjected to a logarithmic (log_{10}) transformation prior to statistical analysis.

3.4.5.3 Cardiac vagal control

The HRV (measure of cardiac vagal control) was obtained from the HR activity during the executive function tasks (3 min and 30 sec in total). Artefacts were filtered out using the automatic medium filter. Thereafter, high frequency (HF-HRV) power (0.15-0.4 Hz) in msec was obtained using fast Fourier transform (Tarvainen et al., 2014), which was then subjected to logarithmic (log10) transformation. *Reactivity* measures of HF-HRV (pre-test and post-test) were determined by calculating the differences between the HRV during the baseline and executive function task performance (Laborde et al., 2018; Laborde, Mosley, & Thayer, 2017).

3.4.5.4 Statistical approach

VASf scores were subjected to a 2 x 3 repeated measure analysis of variance (ANOVA): Group (Fatigue, Non-fatigue) x Test (Baseline, Pre-, Post-). Performance, theta power and *reactivity* HF-HRV during the executive function tasks were all subjected to 2 x 2 repeated measure analyses of variance (ANOVA): Group (Fatigue, Non-fatigue) x Test (Pre-, Post-). An independent t-test was used to compare between-group scores on the NASA-TLX scale.

Sphericity and normality checks were performed, and controlled for when needed. When main effects or interactions were found, separate ANOVAs were conducted and post-hoc tests were Bonferroni corrected. Effect sizes are reported as partial η squared (η_p^2), with the values.01, .06 and .14 indicating relatively small, medium and large effects sizes, respectively (Cohen, 1988). The statistical tests

were performed using SPSS (IBM, version 25.0) computer software. Significance was set at $p = .05$ for all statistical tests.

3.5 Results

3.5.1 Feelings of fatigue

For VASf, a main effect of Group was not evident, $F(1,51) = 2.88$, $p = .096$, $\eta_p^2 = .05$, but a main effect of Test was found, $F(1.75,89.34) = 12.42$, $p < .001$, $\eta_p^2 = .20$. Post-hoc analysis revealed higher scores for the post-test compared to both the baseline ($p < .010$) and the pre-test ($p < .001$), which did not differ ($p = 1.00$). Further insight into the Test effect was revealed by a Group x Test interaction, $F(2,102) = 3.41$, $p = .037$, $\eta_p^2 = .06$ (see Figure 3.5). Follow-up repeated measure ANOVAs for each group separately revealed no differences across Test in the non-fatigued (control) group, $F(2,50) = 1.92$, $p = .157$, $\eta_p^2 = .07$, but significant differences were evident in the fatigued group, $F(1.54,40.03) = 12.81$, $p < .001$, $\eta_p^2 = .33$. Post-hoc analysis showed that scores in the fatigued group were significantly higher in the post-test compared to both the baseline ($p < .010$) and pre-test ($p < .001$), which did not differ ($p = 0.427$).

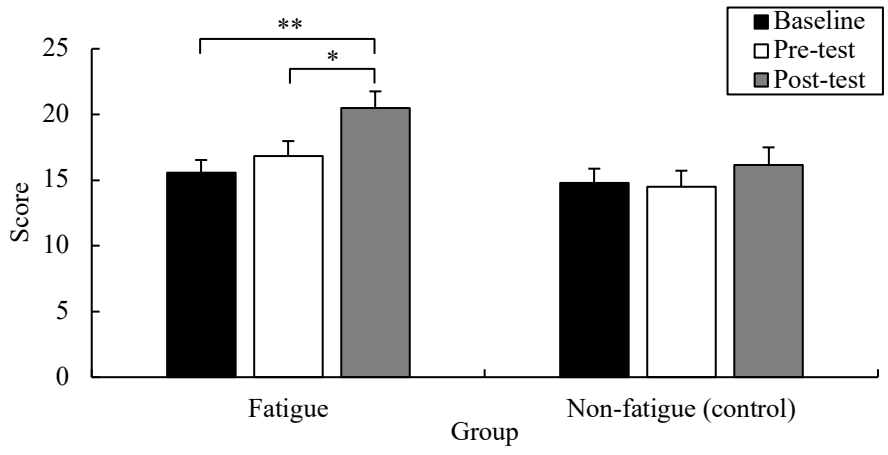

Figure 3.5 Mean score on the Visual Analog Scale of fatigue (VASf) for each group at baseline, pre-test and post-test. Error bars represent standard error of the mean. *$p < .05$, **$p < .001$.

3.5.2 Mental effort

Score on the NASA-TLX (administered at post-test) was significantly higher in the fatigued group (mean = 76.97, SD = 13.18) compared to the non-fatigued (control) group (mean = 53.75, SD = 23.84), $t(41.79) = 4.53$, $p < .001$, $\eta_p^2 = .28$.

3.5.3 Executive functions

3.5.3.1 Inhibition

For the Stroop task inhibition-cost$_{score}$ (see formula in Method),[19] neither a main effect of Group, $F(1,46) = 0.04$, $p = .840$, $\eta_p^2 < .01$, nor of Test, $F(1,46) = 1.12$, $p = .295$, $\eta_p^2 = .02$, was revealed. A Group x Test interaction was evident, $F(1,46) = 4.130$, $p = .048$, $\eta_p^2 = .08$ (see Figure 3.6). Separate post-hoc tests for each group revealed that inhibition-cost$_{score}$ was significantly lower (i.e., better performance) in the non-fatigued (control) group during the post-test compared to the pre-test ($p = .032$), but not in the fatigued group ($p = .506$).

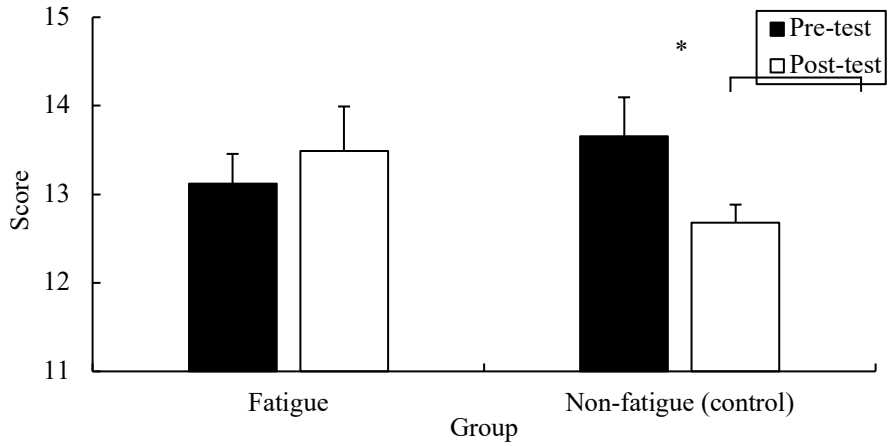

Figure 3.6 Inhibition-cost$_{score}$ for the Stroop task for each group at pre-test and post-test. The higher the inhibition-cost$_{score}$ the higher the number of attempts needed to complete the interference block (i.e., worse performance). Error bars represent standard error of the mean. *$p < .05$.

For the inhibition-cost$_{duration}$, neither a main effect of Group, $F(1,44) = 0.73$, $p = .398$, $\eta_p^2 = .02$, nor of Test, $F(1,44) = 1.98$, $p = .167$, $\eta_p^2 = .04$, was revealed. A

[19] Logarithmic (log10) transformation was performed to control for skewness (Troyer et al., 2006).

Group x Test interaction was not evident, F(1,44) = 0.53, p = .469, η_p^2 = .01 (see Table 3.1).

3.5.3.2 Switching

For Plus-Minus switching-cost$_{score}$ (see formula in Method),[20] neither a main effect of Group, F(1,53) = 2.96, p = .091, η_p^2 = .05, nor of Test, F(1,53) = 3.11, p = .083, η_p^2 = .06, was found. However, a Group x Test interaction was evident, F(1,53) = 4.73, p = .034, η_p^2 = .08 (see Figure 3.7). Post-hoc analysis for each group revealed that the switching-cost$_{score}$ was significantly lower (i.e., better performance) in the non-fatigued (control) group during the post-test compared to the pre-test, (p = .010) but not in the fatigued group (p = .773).

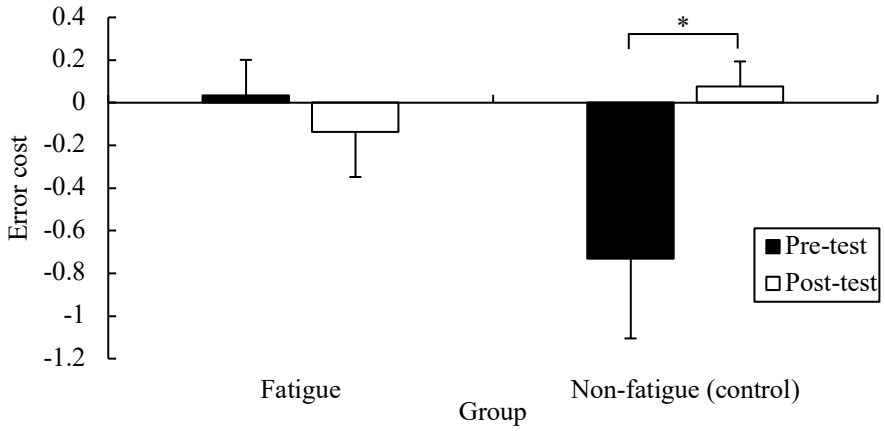

Figure 3.7 Switching-cost$_{score}$ for the Plus-Minus task for each group at pre-test and post-test. The higher the switching-cost$_{score}$ the higher the score for the switching block, compared to the addition and subtraction blocks. Error bars represent standard error of the mean. *p < .05.

For the Plus-Minus switching-cost$_{duration}$, significant main effects were not found for Group, F(1,52) = 0.14, p = .713, η_p^2 < .01, or for Test, F(1,52) = 0.19, p = .665, η_p^2 < .01, and there was no Group x Test interaction, F(1,52) = 2.19, p = .145, η_p^2= .04 (see Table 3.1).

For the Plus-Minus switching-cost$_{RT,}$ neither a main effect of Group, F(1,51) = 0.70, p = .407, η_p^2 = .01, nor of Test, F(1,51) = 1.47, p = .232, η_p^2 = .03, was evident. However, there was a Group x Test interaction, F(1,51) = 4.37, p = .041,

[20] Logarithmic (log10) transformation was performed to control for skewness (Templeton, 2011).

η_p^2= .08 (see Figure 3.8). Separate post-hoc tests for each group revealed that switching-cost$_{RT}$ was significantly lower (i.e., better performance) in the non-fatigued (control) group during the post-test compared to the pre-test (p = .036), but not in the fatigued group (p = .511).

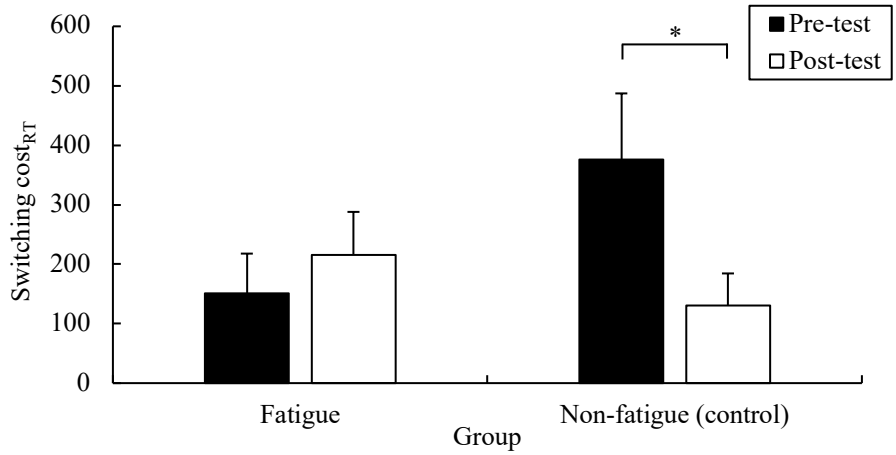

Figure 3.8 Switching-cost$_{RT}$ for the Plus-Minus task for each group at pre-test and post-test. The higher the switching-cost$_{RT}$ the higher the median RT for the switching block, compared to the addition and subtraction blocks. Error bars represent standard error of the mean. *p < .05.

3.5.3.3 Updating

For the N-back scores,[21] main effects were not evident for Group, F(1,39)= 1.84, p = .183, η_p^2 = .05, or for Test, F(1,39) = 2.56, p = .118, η_p^2 = .06. An interaction was not present, F(1,39) = 0.05, p = .824, η_p^2 < .01 (see Table 3.1).

For RTs, main effects were not evident for Group, F(1,39) = 2.62, p = .114, η_p^2 = .06, or for Test, F(1,39) = 0.77, p = .387, η_p^2 = .02. An interaction was not present, F(1,39) = 0.07, p = .792, η_p^2 < .01 (see Table 3.1).

3.5.4 EEG power

3.5.4.1 Inhibition

For EEG theta power in the Fz region during the Stroop task, main effects were not found for Group, F(1,27) = 0.41, p = .529, η_p^2 = .02, or for Test, F(1,27) = 0.51, p

[21] Logarithmic (log10) transformation was performed to control for skewness (Engelhardt, Harden, Tucker-Drob, & Church, 2019).

= .482, η_p^2 = .02. However, a Group x Test interaction was present, F(1,27) = 6.51, p = .017, η_p^2 = .19 (see Figure 3.9). Separate post-hoc tests for each group revealed that theta power was significantly lower during the post-test compared to the pre-test in the non-fatigued (control) group (p = .045), but not in the fatigued group (p = .188).

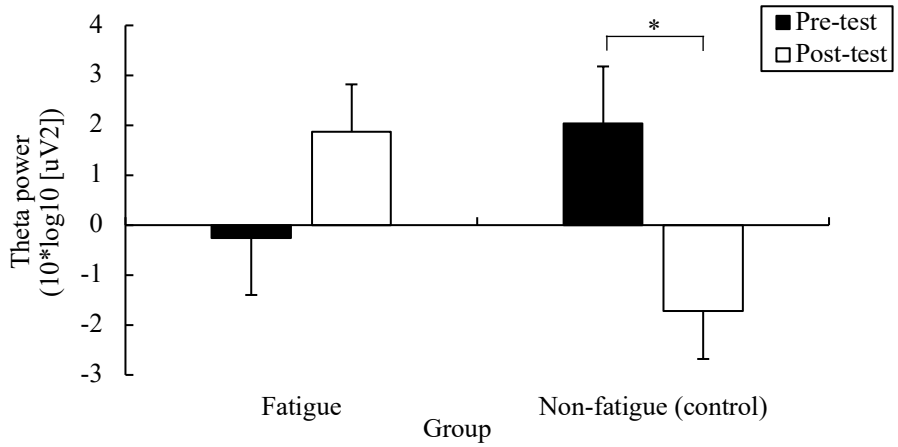

Figure 3.9 Mean theta (4-7 Hz) power for each group during the Stroop task at pre-test and post-test. Error bars represent standard error of the mean. *p < .05.

3.5.4.2 Switching

Neither a main effect of Group, F(1,29) = 1.32, p = .260, η_p^2 = .04, nor of Test, F(1,29) = 1.02, p = .321, η_p^2 = .03, was evident for Fz theta power during the Plus-Minus task. A Group x Test interaction was not evident, F(1,29) = 0.03, p = .856, η_p^2 < .01 (see Table 3.1).

3.5.4.3 Updating

No main effect of Group, F(1,26) = 0.23, p = .638, η_p^2 = .01, or of Test, F(1,26) = 0.01, p = .927, η_p^2 < .001, was evident for the Fz theta power during the N-back task, and a Group x Test interaction was not found, F(1,26) = 1.88, p = .183, η_p^2 = .07 (see Table 3.1).

3.5.5 Cardiac vagal control

The *reactivity* HF-HRV measure revealed no main effects for Group, F(1,45) = 2.08, p =.157, η_p^2 = .04, or Test, F(1,45) = 0.52, p = .475, η_p^2 = .01. A Group x Test interaction was not present, F(1,45) = 0.01, p = .931, η_p^2 < .01 (see Table 3.1).

Table 3.1 Mean and SD values of the non-significant results for measures in Experiment 2a, per group and test.

Group	Fatigue				Non-fatigue (control)			
	Pre-test		Post-test		Pre-test		Post-test	
	M	SD	M	SD	M	SD	M	SD
Inhibition-cost$_{duration}$	18.07	9.47	17.09	5.21	20.85	10.57	17.75	7.34
Switching-cost$_{duration}$	1.44	5.65	2.56	5.43	3.28	5.42	1.42	3.50
Updating score	11.50	0.69	20.75	1.62	11.62	0.74	21.14	0.96
Updating RT	757.6	175.2	703.5	170.7	844	301	815.1	303.3
Theta Fz power: Switching	0.70	3.93	4-0.6	4.95	-1.09	6.83	-2.02	3.42
Theta Fz power: Updating	-1.27	5.10	0.85	5.41	-0.12	8.53	-1.97	4.51
HRV	-0.16	0.41	-0.19	0.38	-0.01	0.35	-0.03	0.35

3.6 Discussion

The cognitive fatigue task caused increased feelings of fatigue and greater mental effort was reported by participants in the cognitive fatigue treatment than participants in the control treatment. With respect to executive functions of working memory, both inhibition and switching performance improved significantly from pre-test to post-test in the non-fatigued (control) group, suggesting that a learning effect occurred. No such improvements occurred in the fatigued group, so the cognitive fatigue task may have interfered with both inhibition and switching, as hypothesised. Updating, as represented by performance on the N-back task, showed no differential effects in the two groups, suggesting that updating was unaffected by cognitive fatigue. Previous studies suggest that the updating function relies on different cognitive processes compared to inhibition and switching functions (Imburgio & Orr, 2018; St Clair-Thompson, 2011; Zhang et al., 2015). Zhang et al. (2015), for example, suggested that the inhibition and switching functions are

related to cognitive flexibility, whereas updating is related to cognitive stability. Cognitive flexibility is suggested to reflect adaptability to the changing environment, whereas cognitive stability is suggested to reflect goal maintenance (Frober, Raith, & Dreisbach, 2018). This implies that our cognitive fatigue task primarily depleted cognitive flexibility.

We predicted that Fz theta power during the executive function tasks would increase from pre-test to post-test in the cognitively fatigued group compared to the non-fatigued (control) group. Fz theta power was not significantly different between groups during switching or updating, but during the inhibition task, a group by test interaction was evident. Theta power increased from pre-test to post-test among participants in the fatigued group (although not significantly). However, theta power decreased significantly from pre-test to post-test in the non-fatigued (control) group. There is debate regarding how changes in Fz theta power during cognitive tasks should be interpreted, with some studies claiming that changes in theta power may be associated with engagement in the task, and others claiming that changes may be associated with recruitment of mental resources (see Wascher et al., 2014, for a discussion on this). Decreased Fz theta power at post-test in the non-fatigued group implies that participants recruited fewer mental resources during the executive function tasks, perhaps because of familiarity or learning effects. Participants in the non-fatigued (control) group displayed improved performance of the executive functions tasks in the post-test, which supports this possibility. Additionally, previous research has shown that good cognitive performance is associated with reduced Fz theta power (Klimesch, 1999). In contrast, higher Fz theta power at post-test in the cognitively fatigued group may indicate that participants recruited additional mental resources to compensate for the effects of fatigue on the executive functions of working memory. This explanation is supported by the fact that participants displayed stable performance of the executive function tasks when they were fatigued (i.e., post-test).

HRV was used as an indirect measure of working memory activity based on the neurovisceral integration model (Hansen et al., 2003; Thayer et al., 2009). We expected HRV to be lower during the executive function tasks post-fatigue compared to pre-fatigue, and compared to no fatigue (control). However, no significant effects were found. Recent studies have reported that HRV responses

can differ as a function of specific executive functions (Jennings, Allen, Gianaros, Thayer, & Manuck, 2015; Kimhy et al., 2013; Laborde et al., 2018), so it would be of interest to examine HRV during specific executive function in future studies.[22]

Previous studies suggest that inhibition and switching (i.e., cognitive flexibility) are the main functions utilized for processes, such as rumination and reinvestment[23] (Park et al., 2020; Yang, Cao, Shields, Teng, & Liu, 2017), and also for associated verbal-analytical processes like hypothesis testing (Masters & Maxwell, 2008; Niebauer, 2004). Consequently, we concluded that the motor specific cognitive fatigue task that we developed has potential to suppress working memory activity and therefore disrupt or reduce verbal-analytical engagement (and thus hypothesis testing) in more complex, goal driven movements, such as those employed during sports.

3.7 Experiment 2b

Having established the efficacy of our cognitive fatigue task by revealing increased feelings of fatigue and moderation of executive functions, we therefore investigated whether the intervention caused reduced hypothesis testing during practice of an adapted shuffleboard task. The task required participants to use a paddle to slide a disk to a given target. The contours of the paddle were shaped to allow participants to use many different solutions for the task. Behavioural and psychophysiological measures were obtained to determine the extent of hypothesis testing. The behavioural measures consisted of self-ratings of technique (Maxwell et al., 2001; Maxwell, Masters, & Poolton, 2006), number of paddle solutions and number of technique changes (Maxwell et al., 2001).

The psychophysiological measures consisted of two cortical measures of high-alpha EEG power over the left temporal (T7) region and connectivity between T7 and the mid-frontal (Fz) regions, to examine verbal-analytical engagement

[22] We were unable to analyse HRV separately for inhibition, switching and updating because the task durations were too short brief for reliable analysis (average duration 1 min and 40 sec) (Laborde et al., 2017).

[23] Reinvestment is defined as the conscious manipulation of explicit knowledge by working memory, to control movements (Masters & Maxwell, 2008).

during movement, which we predicted to be associated with hypothesis testing (Maxwell et al., 2001).

The T7 region place an important role in processing verbal-analytical knowledge (Kaufer & Lewis, 1999; Sperry, 1974), and neural activation of the T7 area has been used to indirectly gauge verbal-analytical processes during motor task performance (Hatfield et al., 1984; Haufler et al., 2000; Kerick et al., 2001; van Duijn et al., 2019). Specifically, these studies have revealed that increased high alpha power (10-12 Hz)[24] over the T7 region during motor planning is associated with lower levels of verbal-analytical processes (Hatfield et al., 1984; Haufler et al., 2000; Kerick et al., 2001; van Duijn et al., 2019).

The Fz region is near the motor areas deputed to motor planning (Cooke et al., 2015; Shibasaki & Hallett, 2006). Based on this, previous studies have computed connectivity between the T7 and Fz regions (i.e., high-alpha T7-Fz connectivity) to measure the extent of verbal-analytical engagement in motor planning (Cooke, 2013; Gallicchio et al., 2016; Hatfield & Hillman, 2001; Zhu, Poolton, Wilson, Maxwell, et al., 2011). Zhu, Poolton, Wilson, Maxwell, et al. (2011), for example, revealed that during movement preparation (4 sec before movement initiation) participants with a lower propensity to consciously control their movements[25] displayed lower T7-Fz connectivity compared to participants with a higher propensity to consciously control their movements. Based on this evidence, T7 power and T7-Fz connectivity are potentially valuable markers of the effect of cognitive fatigue on hypothesis testing in a motor task (see Cooke, 2013; Hatfield & Hillman, 2001, for reviews).

We hypothesized that the cognitive fatigue task would suppress the inhibition and switching functions of working memory during the adapted shuffleboard task, compared with the non-fatigued (control) group, thus interfering with the ability to test hypotheses about performance. Consequently, we expected that in the cognitively fatigued group participants would self-report fewer technique changes, test fewer paddle solutions and display fewer technique changes than

[24] High-alpha power is inversely related to neural activity (e.g., Gallicchio et al., 2017; Klimesch, 1999).

[25] Conscious control was measured by the Movement Specific Reinvestment Scale (Masters et al., 2005; Masters & Maxwell, 2008).

participants in the non-fatigued (control) group. They were also expected to display lower levels of T7-Fz connectivity and higher high alpha T7 power.

3.8 Method

3.8.1 Participants and Design

See Participants and Design, Experiment 2a. Participants who completed the fatigue or non-fatigue (control) treatment in Experiment 2a remained in the laboratory and immediately completed the adapted shuffleboard task.

3.8.2 Shuffleboard Task

After cognitive fatigue/control participants were required to practice shuffling a wooden disk (50 x 13 mm) to a target circle (diameter 10 cm) positioned at a distance of 2 m on a board, using a wooden paddle (see Figure 3.10). The contours of the paddle were shaped inconsistently to provide participants many different methods by which to direct the disk to the target. The number of different methods used was adopted as an objective measure of hypothesis testing. The target was projected onto the board by an overhead projector and a camera above the target captured the outcome position of the disk after each trial. A video camera was used to capture the movements of the participant during each trial.

Figure 3.10 Shuffleboard disk and paddle.

3.8.3 Measures

3.8.3.1 Shuffleboard performance

Radial error (cm) was obtained as a performance measure. Radial error represented the distance between the final position of the disk and the centre of the target. *ScorePutting* software (written in National Instruments LabVIEW) was used to compute the radial error from a photograph taken with a camera that was placed directly above the target (Neumann & Thomas, 2008).

3.8.3.2 Behavioural measures of hypothesis testing

Participants were asked to rate how motivated they were to perform the shuffleboard task (scale 1–10), in order to control for potential influences of motivation on task performance (Boksem et al., 2006). No significant differences in motivation were revealed between Group, t(53) = -1.295, p = .201, d = 0.35.

Self-reported technique changes were conducted by asking the participants to rate how often they changed their technique during each block of twenty trials (scale 1–10). Additionally, two researchers blinded to treatment group independently viewed the video data and counted the number of paddle solutions and the number of changes in technique during each block of trials. Paddle solutions were defined as the different ways in which the paddle was used (see Figure 3.10), and changes in technique were defined as the different ways in which the paddle was moved. A high degree of correlation was evident between the scores of the two researchers for both measures - $ICC_{average\ measures\ stick}$ = 0.80, 95% confidence interval 0.29-0.94, F(11,11) = 4.92, p = .007 and $ICC_{average\ measures\ technique}$ = 0.86, 95% confidence interval 0.33-0.94, F(11,11) = 5.16, p = .006 (Hallgren, 2012).

3.8.3.3 Psychophysiological measures of hypothesis testing

EEG data was examined during the motor preparation phase of each trial of the shuffleboard task. The EEG data was obtained and processed using the same protocol as in Experiment 2a (see Methods). Participants rested their head on a chin rest prior to each trial and were asked to only focus on the target (to reduce eye movements). They were instructed to remain as still as possible during when performing the task. Participants started preparing the movement when the disk was placed in front of them and initiated their movement when the target appeared on

the board. EEG activity was determined for the high alpha frequency band (10-12 Hz), as this frequency is associated with global cortico-communication (Klimesch, 1999).

3.8.4 Procedure

Participants rated their motivation before starting the shuffleboard task, which consisted of three blocks of 20 shuffleboard trials (block took an average of 6 min and 40 sec to complete). Participants were instructed to slide the disk onto the target as accurately as possible and to initiate their movement when the target appeared on the table. The position of the disk was recorded by photograph after each trial. The target then disappeared and the researcher collected the disk and presented it for the next trial. This was done to standardise the inter-trial interval and to reduce the need for participants to move between trials. When the final block of practice trials was completed, participants completed a self-report rating of the number of technique changes they had made in each block of trials.

3.8.5 Data analysis

3.8.5.1 EEG connectivity and power measures

The EEG data was analysed by first generating epochs consisting of 5 sec prior until 2 sec after the target appeared (i.e., movement initiation) for each trial. Thereafter, the same filtering and cleaning procedures as Experiment 2a were applied to the epochs (see Experiment 2a, Methods section for more details). A threshold-based artefact removal procedure was performed, deleting epochs with values ± 75 μV to clean the signal (Deeny et al., 2003). Exclusion of participants from further analysis occurred if too many epochs (more than 25%) had to be deleted.[26] The alpha frequency band (8-12 Hz) was adjusted for each participant based on their individual alpha frequency (IAF) peak, determined from the baseline measure described in Experiment 2a (IAF toolbox, Corcoran et al., 2018). The clean signal was then subjected to time frequency analysis to obtain estimated instantaneous high alpha frequency power for 3 sec prior to movement initiation.

[26] Due to technical issues with the EEG equipment, twenty-one participants had to be excluded from this analysis (19 participants were retained in each group).

Phase angles were also obtained from the time frequency analysis and were used to compute inter-site phase clustering connectivity (ISPC, Cohen, 2014) between the left temporal (T7) and frontal (Fz) regions in the high alpha frequency band for the 3 sec prior to movement initiation. We calculated the $ISPC_{trial}$ using the following function: [27]

$$ISPC_{xy}(f) = \left| n^{-1} \sum_{t=1}^{n} e^{i(\theta_x(tf) - \theta_y(tf))} \right|$$

N is the number of data points, *i* is the imaginary operator, θ_x and θ_y are the phase angles of the recorded signal at two different scalp locations, *t* is the trial and *f* is the frequency bin. The $e^{i(\theta_x(tf) - \theta_y(tf))}$ represents the complex vector with magnitude 1 and angle θ_x - θ_y, $n^{-1} \sum_{t=1}^{n}(.)$ denotes averaging over time points, and $|.|$ is the module of the averaged vector (Cohen, 2014; Lachaux et al., 1999). ISPC is assigned as a value between 0 (no functional connection) and 1 (perfect functional connection). Finally, a Z-transformed (inverse hyperbolic tangent) was performed to ensure normal distribution (e.g., Gallicchio et al., 2016; Zhu, Poolton, Wilson, Maxwell, et al., 2011).

3.8.5.2 Statistical approach

All measures were subjected to a 2 x 3 repeated measures ANOVA: Group (Fatigue, Non-fatigue) x Block (Block 1, Block 2, Block 3). Sphericity and normality checks were performed and controlled for when necessary. Separate ANOVAs with Bonferroni corrections were performed when main effects or interactions were found. Effect sizes are reported as partial η squared (η_p^2), with the values .01, .06 and .14 indicating relatively small, medium and large effect sizes, respectively (Cohen, 1988). The statistical tests were performed using SPSS (IBM, version 25.0) computer software. Significance was set at $p = .05$ for all statistical tests.

[27] Cohen (2014) suggests that the $ISPC_{trial}$ measure is appropriate when there is a high number of trials (e.g., 40 trials or more).

3.9 Results

3.9.1 Behavioural measures of hypothesis testing

3.9.1.1 Self-reported technique changes

No main effect was found for Group, $F(1,55) = 0.26$, $p = .610$, $\eta_p^2 = .01$, but there was a main effect for Block, $F(1.47,81.03) = 26.33$, $p < .001$, $\eta_p^2 = .32$ (see Figure 3.11). Post-hoc analysis revealed that participants reported that they made more changes in Block 1 compared to Block 2 ($p = .003$) and Block 3 ($p < .001$), with more changes in Block 2 than Block 3 ($p < .001$). A Group x Block interaction was not present, $F(2,110) = 0.01$, $p = .988$, $\eta_p^2 < .01$.

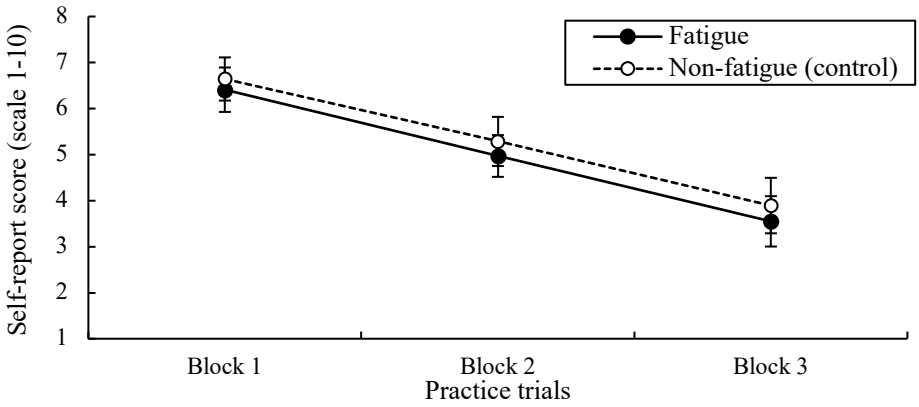

Figure 3.11 Mean score on the self-report of technique change for each group by block of trials. Error bars represent standard error of the mean.

3.9.1.2 Number of paddle solutions

A main effect was not present for Group, $F(1,52) = 0.13$, $p = .717$, $\eta_p^2 < .01$, but an effect was present for Block, $F(1.79,92.79) = 37.07$, $p < .001$, $\eta_p^2 = .42$ (see Figure 3.12). Post-hoc analysis revealed that participants used significantly more solutions in Block 1 compared to Block 2 ($p < .001$) and Block 3 ($p < .001$), and more solutions in Block 2 than Block 3 ($p = .005$). A Group x Block interaction was not present, $F(2,104) = 0.05$, $p = .953$, $\eta_p^2 < .01$.

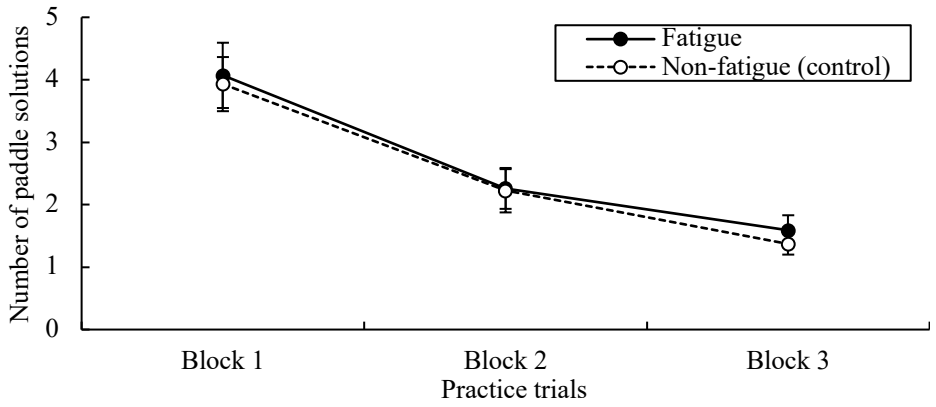

Figure 3.12 Mean number of paddle solutions for each group by block of trials. Error bars represent standard error of the mean.

3.9.1.3 Technique changes

A main effect of Group was evident, $F(1,51) = 4.69$, $p = .035$, $\eta_p^2 = .08$ (see Figure 3.13), indicating significantly more technique changes in the fatigued group than the non-fatigued (control) group over the three blocks of trials. A main effect was also evident for Block, $F(1.67,85.05) = 25.12$, $p < .001$, $\eta_p^2 = .33$, with post-hoc analysis revealing a significantly higher number of technique changes in Block 1 compared to Block 2 ($p < .001$) and Block 3 ($p < .001$). Block 2 and Block 3 were not significantly different ($p = 1.00$). An interaction between Group and Block was absent, $F(2,102) = 0.55$, $p = .580$, $\eta_p^2 = .01$.

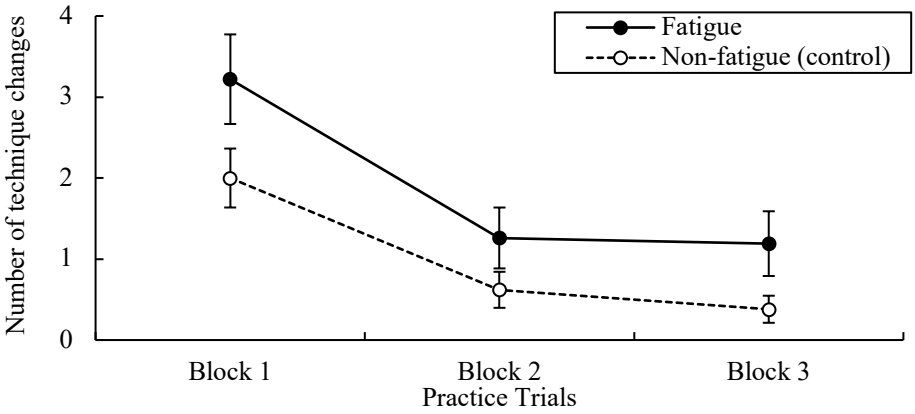

Figure 3.13 Mean number of technique changes for each group by block of trials. Error bars represent standard error of the mean.

3.9.2 Psychophysiological measures of hypothesis testing

3.9.2.1 T7-Fz connectivity

A main effect was found for Group, $F(1,32) = 5.83$, $p = .022$, $\eta_p^2 = .15$ (see Figure 3.14), indicating significantly higher T7-Fz connectivity in the fatigued group than the non-fatigued (control) group over the three blocks of trials. Neither a main effect of Block, $F(2,64) = 1.18$, $p = .315$, $\eta_p^2 = .04$, nor a Group x Block interaction, $F(2,64) = 1.09$, $p = .344$, $\eta_p^2 = .03$, were present.

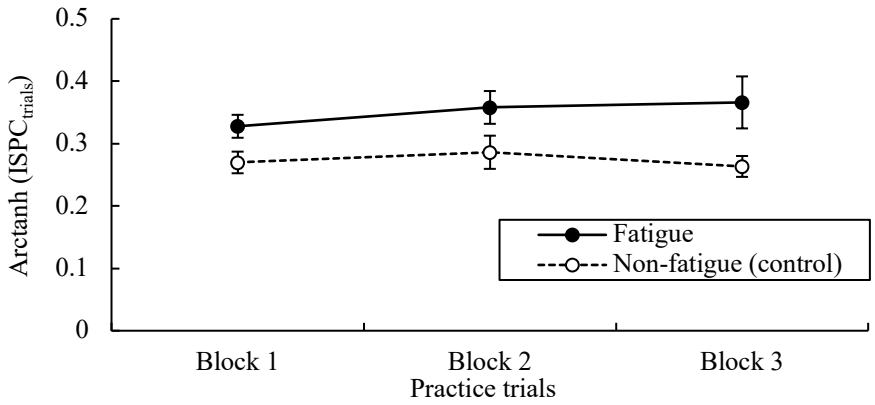

Figure 3.14 Mean ISPCtrials connectivity for each group by block of trials. Error bars represent standard error of the mean.

3.9.2.2 T7 high alpha power

Main effects were not present for Group, $F(1,32) = 0.70$, $p = .408$, $\eta_p^2 = .02$, or for Block, $F(2,64) = 1.78$, $p = .177$, $\eta_p^2 = .05$. A Group x Block interaction was not present, $F(2,64) = 1.99$, $p = .145$, $\eta_p^2 = .06$ (see Table 3.2 for mean and SD values).

Table 3.2 Mean and SD value for high alpha T7 power in each group by block.

Group	Fatigue		Non-fatigue (control)	
	M	SD	M	SD
Block 1	-0.32	1.18	0.43	0.59
Block 2	0.56	1.32	0.32	0.89
Block 3	0.43	0.85	0.56	1.63

3.9.3 Shuffleboard performance

A main effect of Group was not evident for radial error, $F(1,50) = 3.53$, $p = .066$, $\eta_p^2 = .07$. A main effect of Block was evident, $F(1.81,90.52) = 79.19$, $p < .001$, $\eta_p^2 = .61$ (see Figure 3.15). Radial error was significantly higher in Block 1 compared to Block 2 ($p < .001$) and Block 3 ($p < .001$), and higher in Block 2 compared to Block 3 ($p = .002$). A significant interaction was not revealed, $F(2,100) = 1.08$, $p = .344$, $\eta_p^2 = .02$.

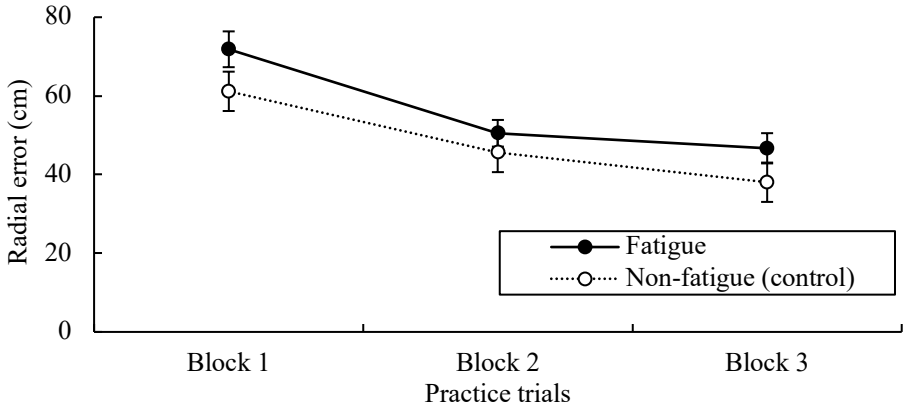

Figure 3.15 Mean radial error (cm) for each group by block of trials. Error bars represent standard error of the mean.

3.10 Discussion

Behavioural measures of hypothesis testing suggested that participants tested more hypotheses in the first block of the shuffleboard task compared with the later blocks. This is consistent with traditional views of learning (e.g., Fitts & Posner, 1967), which suggest that as learning progresses processing of performance becomes less cognitive.

We found no between-group differences in self-reported changes in technique or in the number of paddle solutions that participants used, although more technique changes occurred in the fatigued group. It is possible that participants were unaware of the way in which they altered their kinematics during performance and thus under-reported their technique changes. Furthermore, it has been argued that the assessment of declarative knowledge via self-report should consist of a

qualitative analysis of the information produced by the participants, rather than by a simple Likert scale as used in this study (Shanks & John, 1994). It is also possible that participants did not use many different paddle solutions, but instead chose to alter their technique leveraging the flexibility of the human kinematic system.

The technique changes, however, suggest that the cognitive fatigue task did not supress hypothesis testing; in fact, hypothesis testing increased. Consistent with this finding, high alpha power for the T7 region was not significantly different between the fatigued and non-fatigued group, suggesting that verbal-analytical activity in general (e.g., self-talk) was the same, but verbal-analytical engagement in motor performance (i.e., increased high alpha T7-Fz connectivity) was significantly higher in the fatigued group across all shuffleboard blocks.

Performance accuracy (radial error) improved during practice, but was not different between groups. A limitation of the experiment is that we did not include a shuffleboard baseline measure and therefore, we cannot fully discount that the increased verbal-analytical engagement in the task for the fatigued group might be a result of shuffleboard capabilities. However, a baseline shuffleboard task may allow an opportunity to accumulate explicit knowledge on the task, which would have confounded our measures of hypothesis testing.

In contrast to our expectations, participants in the fatigued group did not appear to learn the shuffleboard task implicitly; they displayed more technique changes (indicative of testing more hypotheses) and showed higher levels of verbal-analytical engagement in the motor task compared to non-fatigued participants.

3.11 General Discussion

Chapter 2 revealed that a computer-based cognitive fatigue task did not deplete cognitive resources needed for hypothesis testing during complex movements. They concluded that the cognitive fatigue task that they employed was not sufficiently mentally demanding to reduce verbal-analytical engagement during complex motor skills, and suggested that a more movement-specific cognitive fatigue task should be developed. Based on Chapter 2, we designed a cognitive fatigue task that was motor focused and which challenged information processing (i.e., executive functions of working memory).

In the first stage of the experiment, we found that participants in the cognitively fatigued group reported feelings of greater fatigue and mental effort compared to participants in the non-fatigued (control) group. Of the three executive functions of working memory, the inhibition and switching functions were disrupted by the cognitive fatigue task, but the updating function was not. Differences in Fz theta power (i.e., prefrontal cortex activity) were only found during inhibition. Nevertheless, previous studies have argued that inhibition and switching are most important for hypothesis testing (Park et al., 2020; Yang et al., 2017), so we concluded that the motor specific cognitive fatigue task had potential to reduce verbal-analytical engagement in motor performance and thus cause implicit motor learning by suppressing executive functions associated with hypothesis testing.

Subsequently, the second part of the study examined whether the motor specific cognitive fatigue task, indeed, suppressed hypothesis testing during practice of a novel motor skill. However, in contrast to our expectations, a higher number of changes in technique occurred in the fatigued group compared to the non-fatigued (control) group during practice of the shuffleboard task. Technique changes are thought to reflect hypothesis testing, with performers altering their movements in order to become more successful at the task. Consistent with this, participants in the fatigued group also displayed greater verbal-analytical engagement in motor planning (T7-Fz connectivity) (e.g., Cooke et al., 2015; Kerick et al., 2001; Zhu, Poolton, Wilson, Maxwell, et al., 2011). These findings suggest that the cognitive fatigue task may have primed the performer to use more cognitive resources during motor performance to compensate for the side effects of fatigue. However, fatigue might have also resulted in disrupted executive functions, causing reduced ability to *inhibit* processing irrelevant information and inefficient *switching* between incoming information. This is consistent with findings of Lorist et al. (2009), who revealed that cognitive fatigue disrupted efficient activation of the areas of the brain that were crucial for effective performance by causing increased neural activity across the whole brain (i.e., reduced interhemispheric inhibition). Consequently, by increasing compensatory effort into motor planning (e.g., trying harder), participants in our study may have inadvertently diverted resources away from critical cortical regions. This may have disrupted efficient

processing of information (disrupted inhibition and switching). This argument is consistent with Hatfield and Hillman (2001) definition of psychomotor efficiency.

Given that Zhu et al. (2015) did claim to have caused implicit motor learning by using tDCS to suppress activity in the prefrontal cortex (i.e., associated with working memory), it is possible that our motor focused cognitive fatigue protocol was not sufficiently stringent to completely suppress working memory functions. Indeed, it seems that our protocol may have increased verbal-analytical engagement in the task as a way to compensate for the fatigue, inefficient though that may be. Future studies should, therefore, utilize more stringent methods to suppress working memory activity prior to motor practice. Hypoxia, for example, has been revealed to reduce available cognitive resources because the body prioritizes support for the cardiac system in reduced oxygen environments (McMorris, Hale, Barwood, Costello, & Corbett, 2017; Yan, Zhang, Gong, & Weng, 2011). However, the results of our study do give insight into how cognitively demanding tasks affect cognitive processes during both computer-based executive function tasks and relatively complex motor tasks. Cognitively fatiguing motor control, using tasks such as ours, may not be desirable if it primes greater verbal-analytical processing of motor skills in novices. However, it may be desirable if it primes greater verbal-analytical processing in experts who are refining their skills (e.g., Toner & Moran, 2014, 2015), or in tasks where successful performance is a function of both motor and cognitive components, such as in Esports (Martin-Niedecken & Schättin, 2020) or surgery (e.g., Masters, Poolton, Abernethy, & Patil, 2008). In tasks like these, cognitive fatigue may prime greater verbal-analytical processing, which might facilitate cognitive components of the task.

Chapter 4

Experiment 3: The effect of unilateral hand contractions on psychophysiological activity during motor performance: Evidence of verbal-analytical engagement[28]

4.1 Abstract

The findings of Experiment 2a & 2b revealed that a motor-related cognitive fatigue task depleted executive functions of working memory, although this caused higher, rather than, lower verbal-analytical engagement in the motor task compared to no fatigue. This finding implies that increased verbal-analytical engagement might be a consequence of less efficient working memory processes. Experiment 3, therefore, examined whether hand contractions are a more efficient method by which to reduce verbal-analytical engagement in performance. In most cases, the left hemisphere of the brain plays an important role in verbal-analytical processing and reasoning, so changes in the balance of hemispheric activation may influence verbal-analytical engagement in movement. Evidence suggests that unilateral hand contractions influence hemispheric activation, but no study has investigated whether there is an associated effect of hand contractions on verbal-analytical processing and psychophysiological activity during motor performance. This study utilized psychophysiological (and behavioural) measures to examine whether pre-performance unilateral hand contraction protocols change verbal-analytical engagement during motor performance. Twenty-eight participants completed three hand contraction protocols in a randomised order: left-hand contractions, right-hand contractions and no hand-contractions. Electroencephalography (EEG) measures of hemispheric asymmetry were computed during hand contractions. A golf putting task was conducted after each protocol. EEG connectivity between sites overlying

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[28] Based on: **Hoskens, M. C. J.,** Bellomo, E., Uiga, L., Cooke, A., & Masters, R. S. W. (2020). The effects of unilateral hand contractions on psychophysiological activity during motor performance: Evidence of verbal-analytical engagement. *Psychology of Sport and Exercise, 48*, 1-8.

the left verbal-analytical temporal region (T7) and the motor planning region (Fz) was computed for the 3 sec prior to movement initiation. Additionally, electrocardiography (ECG) and electromyography (EMG) signals were analysed 6 sec prior to movement initiation until 6 sec after. Golf putting performance (distance from the target) and putter swing kinematics were measured. Contralateral hemisphere activity was revealed for the left-hand and right-hand contractions conditions. During motor planning, the left-hand contraction protocol led to significantly lower T7-Fz connectivity, and the right-hand contraction protocol led to significantly higher T7-Fz connectivity than the other conditions. EMG, ECG and kinematic measures did not differ as a function of condition. Importantly, T7-Fz connectivity mediated the relationship between hand squeezing and motor performance (distance from the target). The EEG results suggest that pre-performance unilateral hand contractions influence the extent of verbal-analytical engagement during motor planning, which in turn influences motor performance. However, the hand contractions did not influence cardiac activity, muscle activity or kinematics.

4.2 Introduction

A link between conscious processes and motor performance is found in studies using electroencephalography (EEG) to examine communication (synchronization) between different regions of the brain (Babiloni et al., 2011; Deeny et al., 2003; Gallicchio et al., 2016; Zhu, Poolton, Wilson, Maxwell, et al., 2011). Evidence from these studies suggests that high conscious engagement in motor performance is associated with more synchronous neuronal activity, indexing greater functional communication between the left temporal T7 region of the brain (involved in verbal-analytical processing), and the frontal midline Fz region of the brain (involved in motor planning) (Babiloni et al., 2011; Deeny et al., 2003; Gallicchio et al., 2016; Zhu, Poolton, Wilson, Maxwell, et al., 2011).

Compelling evidence for the link between conscious control of movements and verbal-analytical processes has been reported by Zhu, Poolton, Wilson, Maxwell, et al. (2011, Experiment 1). They measured propensity to consciously control motor skills using the Movement Specific Reinvestment Scale (MSRS, Masters et al., 2005). Participants with a lower propensity to consciously control

movements displayed lower T7-Fz communication (e.g., coherence) than participants with a higher propensity for conscious control, during the 4 sec preceding golf putts (Zhu, Poolton, Wilson, Maxwell, et al., 2011). Co-activation between the left temporal and frontal regions is also associated with motor performance. For example, Gallicchio et al. (2016) reported that T7-Fz connectivity was lower in the final seconds preceding successful golf putts compared to unsuccessful golf putts, suggesting that reduced or suppressed verbal-analytical processing is a feature of effective motor performance. In sum, reduced left temporal-frontal synchronicity may be associated with less verbal, more procedural, processing of movements.

Attempts to reduce verbal-analytical engagement during motor performance have used neuro-stimulation to suppress activity in the left hemisphere (Landers et al., 1991; Snyder et al., 2003; Zhu et al., 2015). For instance, Zhu et al. (2015) found that cathodal (i.e., inhibitory) transcranial Direct Current Stimulation (tDCS) over the left dorsolateral prefrontal cortex promoted lower verbal-analytical engagement when practicing a golf putting task, compared to sham stimulation (i.e., placebo). However, tDCS is not a practical or accessible training method for the majority of performers, and ethical concerns about such extreme training methods have been raised (Davis, 2013).

Using a slightly less shocking method, Beckmann et al. (2013) and Gröpel and Beckmann (2017) asked semi-professional athletes (gymnastics, soccer, badminton and taekwondo) to squeeze a stress ball in either the left hand or the right hand for 45 sec before performing under competitive pressure. They reasoned that due to the contralateral coupling between our hands and our brain (i.e., the brain area controlling the right hand resides in left hemisphere, and vice-versa), squeezing the right hand should prime the left (verbal-analytic) hemisphere and squeezing the left hand should prime the right (visual-spatial) hemisphere. Results showed that left-hand contractions resulted in more stable performance under pressure than right-hand contractions. The authors argued that left-hand contractions prevented breakdown under pressure by activating the right hemisphere and deactivating the left hemisphere, which reduced disruptive verbal-analytical control of the movements (Beckmann et al., 2013; Gröpel & Beckmann, 2017). Beckmann et al. (2013, Experiment 3) additionally found that right-hand contractions magnified the

effect of pressure, with participants performing worse when they carried out right-hand contractions prior to performing. They suggested that since right-hand contractions activated the left hemisphere, they potentially increased the likelihood that pressure would cause disruptive verbal-analytical engagement in performance. However, it is important to note that this interpretation cannot be confirmed since Beckmann and colleagues did not directly measure cortical activity in their studies.

Studies that did record cortical activity during unilateral hand contractions have revealed inconsistent results. For example, some studies revealed that unilateral hand contractions resulted in lower alpha power (i.e., increased brain activity) in the contralateral hemisphere (Gable et al., 2013; Harmon-Jones, 2006; Peterson et al., 2008; Schiff et al., 1998). However, Cross-Villasana et al. (2015) revealed that unilateral hand contractions produced lower alpha power over both hemispheres. Furthermore, they revealed that immediately after left-hand contractions ceased, whole scalp alpha power increased, indicating widespread deactivation (Cross-Villasana et al., 2015). This latter finding challenges Beckmann and colleagues suggestion that left-hand contractions are beneficial because they activate the right hemisphere. However, it does support the argument that left-hand contractions can deactivate the left hemisphere, perhaps suppressing verbal-analytical engagement in motor planning. Taken together, these findings indicate that hemispheric activity can be altered by hand contraction protocols. However, their effects on verbal-analytical processes have yet to be established. Specifically, no study has examined the effect of unilateral hand contractions on T7-Fz connectivity during the final moments of motor preparation. These final moments are important for establishing the level of conscious monitoring and control of the movement (e.g., Deeny et al., 2003; Gallicchio et al., 2016; Zhu, Poolton, Wilson, Maxwell, et al., 2011). Therefore, measurement of cortical activity, especially T7-Fz connectivity, is required to more rigorously examine the proposed relations between left-hand contractions, verbal-analytical engagement and motor performance.

Finally, no studies have investigated the effects of hand contraction protocols on physiological and kinematic measures that may also relate to verbal-analytical engagement and motor performance outcomes (Cooke et al., 2010). Although Cooke et al. (2014) did not examine hand contractions, they did report

greater heart rate deceleration during the 6 sec preceding motor performance in skilled versus low skilled golfers. Therefore, heart rate deceleration could offer another corroborative physiological measure that is sensitive to the amount of verbal-analytical engagement during motor planning (Cooke et al., 2014; Neumann & Thomas, 2009; Neumann & Thomas, 2011; Radlo, Steinberg, Singer, Barba, & Melnikov, 2002). Similarly, more automatic motor control is also associated with lower muscle activity (Lohse et al., 2010; Vance et al., 2004; Zachry et al., 2005). For example, Lohse et al. (2010) revealed lower muscle activity when participants adopted an external focus of attention while throwing darts, compared to when they consciously monitored their technique. Finally, movement kinematics can also be linked to verbal-analytical engagement in motor planning (Cooke et al., 2014; Malhotra et al., 2015; Masters, Poolton, Maxwell, et al., 2008; Maxwell et al., 2003). For example, Maxwell et al. (2003) revealed that verbal-analytic engagement in motor planning was associated with a less fluid technique. The assessment of such measures alongside T7-Fz connectivity may therefore provide new insight into the mechanisms underpinning the effects of unilateral hand contraction protocols on performance.

The present study is the first to investigate the effect of unilateral hand contraction protocols on psychophysiological and behavioural markers of golf putting performance. The aim was to gain a better understanding of whether pre-performance unilateral hand contractions have an effect on verbal-analytical processes involved in motor performance. Three hand contraction protocols (left-hand contractions, right-hand contractions and no hand-contractions) were performed in a repeated measures crossover design, before performance of a golf putting task. Measures of alpha power (8-12 Hz) between homologous electrode pairs were first computed during the hand contraction protocols to verify that left-hand contractions activated the right hemisphere, and that right-hand contractions activated the left hemisphere. Cortical activity was then examined further by measuring the high-alpha power (10-12 Hz) connectivity level between the verbal-analytical left temporal (T7) region and the motor planning (Fz) region during preparation for each golf putt. Cardiac activity (electrocardiography), muscle activity (electromyography), kinematics, and golf performance were tested as supporting measures of verbal-analytical engagement in motor planning. Mediation

analyses were employed to examine whether our psychophysiological and kinematic indices of verbal-analytic engagement are the mechanisms underpinning any effect of hand contractions on performance.

Based on the behavioural findings of Beckmann et al. (2013) and Gröpel and Beckmann (2017), we predicted that unilateral hand contractions would influence verbal-analytical engagement (i.e., inferred by changes in T7-Fz connectivity) during movement planning. Specifically, we predicted that the left-hand contractions would lower verbal-analytical engagement during motor planning compared to right-hand and no hand-contractions, and that right-hand contractions would raise verbal-analytical engagement in motor planning compared to left-hand and no hand-contractions. Consequently, lower verbal-analytical engagement during the left-hand contraction protocol was expected to promote greater heart rate deceleration, lower muscular activity, smoother kinematics when initiating the golf putt and better outcome performance compared to the right-hand and no hand-contraction protocols (Cooke et al., 2014; Lohse et al., 2010; Neumann & Thomas, 2009; Radlo et al., 2002; Zachry et al., 2005). The opposite effects were predicted for the right-hand contraction protocol. Finally, we predicted that the effects of hand contractions on T7-Fz connectivity and our ECG, EMG and kinematic measures would mediate the relationship between hand contraction protocols and performance.

4.3 Methods

4.3.1 Participants and design

Twenty-eight people were recruited to participate in the experiment. Three participants who had major artefacts in their EEG signal were excluded from further analysis, resulting in a final sample of twenty-five participants (mean age = 26.52, SD = 5.08, female = 15). To control for handedness, only right-handed participants were included (> 70, Edinburgh Handedness Inventory, Oldfield, 1971). All participants had normal/corrected vision. The participants were instructed not to consume alcohol or drugs 24 h prior to testing or caffeine 3 h prior to testing, and to obtain at least 6 h of sleep the night before testing. A repeated measures crossover design was adopted, with participants performing three different protocols (left-hand contractions, right-hand contractions and no hand-contractions). The order of

protocols was counterbalanced within participants. This study was approved by the University (Human) Research ethics committee.

4.3.2 Task

The experiment consisted of a pre-performance hand contraction protocol followed by a golf putting task. The hand contraction protocol required participants to firmly contract a stress ball at a self-paced rate for 45 sec either with their left hand or right hand, or to place their hands on their lap and hold them still for 45 sec (no hand-contractions condition). The researcher instructed the participants to sit quietly and to not talk or make large movements during these protocols, in order to control for muscle activity artefacts.

After each protocol, participants performed 25 golf putts on an artificial grass surface, using a standard length (90 cm) golf putter and a regular-size (diameter 4.7 cm) golf ball. The target was a 1 cm diameter white sticker on the putting surface positioned 2.4 m from the initial starting point.

4.3.3 Measures

4.3.3.1 Psychophysiological measures

EEG data was used to assess cortical activity during the pre-performance hand contraction protocols (e.g., Gable et al., 2013) and during preparation of the golf putts (e.g., Zhu, Poolton, Wilson, Maxwell, et al., 2011). EEG was recorded from thirty-two (32) active electrodes positioned using the 10-20 system (Jaspers, 1958): Fp1, Fp2, AF3, AF4, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, T7, C3, Cz, C4, T8, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, PO3, PO4, O1, Oz, and O2. Additionally, active electrodes were positioned on each mastoid, at the outer canthus and below each eye to record vertical and horizontal electrooculogram (EOG). Monopolar recorded signals were sampled at 1024 Hz, without an online filter, using an ActiveTwo amplifier (Biosemi, The Netherlands).

During the pre-performance protocols, we were primarily interested in cortical asymmetry (i.e., right hemisphere minus left hemisphere) in the broad alpha band frequency (i.e., 8-12 Hz), as previous studies have demonstrated the effects of unilateral hand contractions on broad-band alpha (Cross-Villasana et al., 2015; Gable et al., 2013; Harmon-Jones, 2006; Peterson et al., 2008). During preparation

of the golf putt, we were interested in connectivity in the high-alpha frequency band (i.e., 10-12 Hz), as this portion of the alpha frequency is thought to be specifically related to task specific attentional processes and cortico-communication (see Klimesch, 1999, for a review; Smith, McEvoy, & Gevins, 1999).

Electrocardiography (ECG) was used during golf putting performance, to assess cardiac activity (Cooke et al., 2014; Cooke et al., 2011). Silver/silver chloride spot electrodes (BlueSensor SP, Ambu, Cambridgeshire, UK) were placed on each clavicle and on the lowest left rib. The ECG signal was amplified (Bagnoli-4, Delsys, Boston, MA), filtered (1-100 Hz) and digitized at 2500 Hz with 16-bits resolution (CED Power 1401, Cambridge Electronic Design, Cambridge, UK) using Spike2 software (version 5, Cambridge Electronic Design).

Electromyography (EMG) was used to obtain muscle activity during golf putting for the extensor carpi radialis and flexor carpi ulnaris muscles in the left arm (Cooke et al., 2014; Cooke et al., 2011). Differential surface electrodes (DE 2.1, Delsys) were placed on the belly of the muscles and a ground electrode (BleuSensor SP, Ambu, Cambridgeshire, UK) was placed on the left collarbone. The EMG signal was amplified (Bagnoli-4, Delsys), filtered (20-45 Hz), and digitized at 2500 Hz with 16-bit resolution (Power 1401) using Spike2 software.

4.3.3.2 Golf putting performance measures

The golf putting performance was determined by the mean radial error (cm), representing the mean distance between the final position of the ball and the centre of the target. This measure was computed with *ScorePutting* software (written in National Instruments LabVIEW), which uses the photographs from a camera system directly placed above the targets to control for angle differences (Neumann & Thomas, 2008).

4.3.3.3 Golf kinematics

A triaxial accelerometer (LIS3L06AL, ST Microelectronics, Geneva, Switzerland) and amplifier (frequency response of DC to 15 Hz) were attached to the rear of the putter head in order to measure movement kinematics (Cooke et al., 2014; Cooke et al., 2011). Acceleration of the golf putter from downswing until ball contact was calculated for the x, y and z-axes (representing the lateral, vertical and back-and-

forth movement of the club head), to determine club head orientation, swing height and impact force (Spike2, version 5, Cambridge Electronic Design).

4.3.4 Procedure

Participants were informed about the context of the study and signed an informed consent form prior to the start of the experimental procedure. The EEG, ECG and EMG equipment were set up and a 2 min EEG resting state measurement was performed (1 min open eyes and 1 min closed eyes).

Participants first completed 130 putts as part of a separate investigation of the psychophysiological corollaries of practice (data not reported here). The putts served to familiarise participants with the task. This was followed by performing one of the three pre-performance hand-contraction protocols (left-hand contractions, right-hand contractions or no hand-contractions) while seated. Immediately after each protocol, participants were instructed to stand-up and perform 25 self-paced golf putts, aiming for the target as accurately as possible. The time lag between the end of the squeezing protocol and the start of the golf putting task was approximately 10 sec. A photograph of the final position of the ball was taken after each trial. The researcher then collected the ball and positioned it for the next trial, thereby standardising the inter-trial interval, and reducing the need for participants to move in-between putts. This procedure was repeated for all conditions (three times in total) and took on average 5 min and 53 sec per condition.

4.3.5 Analysis

4.3.5.1 Pre-performance hand contraction protocols

EEG signals captured during the hand contraction protocols were processed offline with EEGLAB software (Delorme & Makeig, 2004) running on MATLAB (Mathwork, Inc., USA version 2018b) to compute the power asymmetry. The signals were first resampled to 250 Hz, re-referenced to the average of all electrodes, and filtered (.01-30 Hz bandpass filter). The IAF toolbox was used to adjust the alpha frequency band for each participant based on their individual alpha frequency peak, determined from the baseline measure (Corcoran et al., 2018).

The signals were then subjected to a threshold-based artefact removal procedure, where any 250 msec window containing signal fluctuations exceeding

±150 μV was rejected (ERPLAB Toolbox, Lopez-Calderon & Luck, 2014). Independent Component Analyses were then performed via the RunICA infomax algorithm (Makeig, Bell, Jung, & Sejnowski, 1996) to identify and remove any remaining artefacts and non-neural activity (e.g., eye-blinks) from the signal. An average of 5.76 components were rejected. The clean signal was then subjected to a time frequency analysis, to obtain the estimate of instantaneous alpha power for the 38 sec of the hand contraction protocols. The total of 45 sec was reduced by 7 sec, due to some participants showing increased artefacts at the end. This analysis was performed by convolving the fast Fourier transform (FFT) power spectrum of the signal with a family of complex Morlet wavelets and eventually taking the inverse FFT (Cohen, 2014). All power values were then log transformed to control for skewness and inter-individual differences. Finally, the transformed values were used to compute the asymmetry scores of the homologous electrode pairs close to the cortical regions involved in hand movements (e.g., Grefkes, Eickhoff, Nowak, Dafotakis, & Fink, 2008): T8-T7, P4-P3, P8-P7, F4-F3, F8-F7, C4-C3, FC2-FC1, FC6-FC5, CP2-CP1, CP6-CP5 (right – left). This is a common way of calculating alpha asymmetry to identify the effects of a state manipulation (e.g., unilateral hand contractions) on the relative activation of the right hemisphere versus left hemisphere of the brain (e.g., Harmon-Jones, 2006). A higher asymmetry score signifies more activity in the left hemisphere (lower alpha power) compared to the right hemisphere (Harmon-Jones, 2006; Wolf et al., 2015).

4.3.5.2 Golf putting task

An optical sensor and microphone were used to mark movement initiation and ball contact in the continuous data (Spike2 and Actiview software, Biosemi), in order to analyse the psychophysiological measures prior to and during the golf putts. The optical sensor (S51-PA-2-C10PK, Datasensor, Monte San Pietro, Italy) was used to identify swing-onset by detecting when the infrared beam was broken by movement of the putter head. The microphone (NT1, Rode, Silverwater, Australia) was linked to a mixing desk (Club 2000, Studiomaster, Leighton Buzzard, UK) to detect putter-to-ball contact.

Connectivity prior to movement initiation was computed offline by processing the EEG signals (EEGLAB software) computed during the golf putt preparation. The signals were cut into epochs of 5 sec (4 sec prior to and 1 sec after

movement initiation). Thereafter, the signals were filtered and cleaned with the same methods as for the *hand contraction protocols*. The signals were then baseline corrected (-.2 to 0 sec, where 0 = movement initiation; Ring et al., 2015) and time-frequency analysis was performed (see *hand contraction protocols, 2.5.1*) to obtain the phase angles. These phase angles were then used to compute connectivity between the left temporal (T7) and frontal (Fz) regions for the 3 sec prior to movement initiation, by calculating inter-site phase clustering (ISPC, Cohen, 2014).[29] We calculated $ISPC_{time}$ measuring phase angle differences across the electrodes over time:[30]

$$ISPC_{xy}(f) = \left| n^{-1} \sum_{t=1}^{n} e^{i(\theta_x(tf)-\theta_y(tf))} \right|$$

N is the number of data points; *i* is the imaginary operator; θ_x and θ_y are the phase angles of the recorded signal at two different scalp locations; *t* is the time point and *f* is the frequency bin. The $e^{i(\theta_x(tf)-\theta_y(tf))}$ represents the complex vector with magnitude 1 and angle θ_x - θ_y ; $n^{-1} \sum_{t=1}^{n}$ (.) denotes averaging over time points, and |.| is the module of the averaged vector (Cohen, 2014; Lachaux et al., 1999). ISPC is given as a value between 0 (no functional connection) and 1 (perfect functional connection). Finally, values were Z-transformed (inverse hyperbolic tangent) to ensure normal distribution (Gallicchio et al., 2016).

The EMG and ECG signals 6 sec prior to until 6 sec after movement initiation were analysed offline in epochs of 1 sec (Cooke et al., 2014; Moore, Vine, Cooke, Ring, & Wilson, 2012; Neumann & Thomas, 2011). Heart rate was corrected for artefacts and R-wave peaks were identified. The intervals between the successive R-waves peaks were calculated and instantaneous heart rate (beats per minute, BPM) was calculated as 6000/(R-R interval). Muscle activity was assessed by rectifying the EMG signal and averaging over 0.5 sec windows, such that the

[29] Two different methods have been used to measure synchronization in the sport science literature. Earlier work (e.g., Deeny et al., 2003) measured magnitude squared *coherence;* however, more recent research has measured inter-site phase *connectivity* (ISPC). ISPC is based on phase information only, which makes it independent of fluctuations in absolute power (Gallicchio et al., 2016).

[30] Cohen (2014) suggests that the ISPC *time* measure is appropriate when having relatively long epochs, with 3 sec considered as long.

mean activity between 6.25 and 5.75 sec prior to movement was used to calculate muscle activity 6 sec before movement, and so on (Cooke et al., 2014).

The acceleration of each putt was determined from the initiation of the downswing phase until the point of contact (Cooke et al., 2014; Cooke et al., 2010; Moore et al., 2012). Average acceleration was calculated for the x, y, and z-axes. Besides impact velocity, Root Mean Square (RMS) jerk and smoothness on the z-axis were computed, as the z-axis is the main axis involved in the putting swing (Cooke et al., 2011; Maxwell et al., 2003).

4.3.5.3 Statistical approach

The cortical activity manipulation check was subjected to a 3 x 10 repeated measures analysis of variance (ANOVA): Condition (Left-hand contractions, Right-hand contractions, No hand-contractions) x Homologous electrode pairs (T8-T7, P4-P3, P8-P7, F4-F3, F8-F7, C4-C3, FC2-FC1, FC6-FC5, CP2-CP1, CP6-CP5). The T7-Fz connectivity measure during preparation of the golf putt was subjected to a one-way ANOVA of Condition (Left-hand contractions, Right-hand contractions, No hand-contractions). Cardiac and muscle activity were subjected to a 3 x 13 repeated measures ANOVA: Condition (Left-hand contractions, Right-hand contractions, No hand-contractions) x Time Bin (-6, -5, -4, -3, -2, -1, 0, +1, +2, +3, +4, +5, +6). Golf kinematics and golf putting performance were both subjected to a one-way ANOVA of Condition (Left-hand contractions, Right-hand contractions, No hand-contractions).

Sphericity was checked and corrected using the Huynh-Feldt correction when necessary. Separate ANOVAs with Bonferroni corrections or polynomial trend analysis were performed when main effects or interactions were found. Effect sizes are reported as partial η squared (η_p^2), with the values .01, .06 and .14 indicating relatively small, medium and large effect sizes, respectively (Cohen, 1988). The statistical tests were performed using SPSS (IBM, version 25.0) computer software. Significance was set at $p = .05$ for all statistical tests.

MEMORE for SPSS (MEdiation and MOderation analysis for REpeated measure designs, Montoya & Hayes, 2017) was used to test within-subject mediation effects on golf putting performance associated with left-hand and right-hand contractions. Mediators were individually tested and included EEG, EMG,

ECG and kinematics (i.e., club head orientation, swing height and impact force). The mediation effect (B), standard error (BootSE) and 95% CI (low and high) were reported (Montoya & Hayes, 2017).

4.4 Results

4.4.1 Manipulation check

The results revealed a main effect of Condition, $F(2,42) = 3.95$, $p = .027$, $\eta_p^2 = .16$, with post-hoc analysis revealing a significantly lower asymmetry score for left-hand contractions compared with right-hand contractions ($p = .015$, see Figure 4.1). No significant effects were revealed for left-hand contractions compared with no hand-contractions ($p = .180$) or right-hand contractions compared with no hand-contractions ($p = 1.00$). No main effect was found for Homologous electrode pairs, $F(3.20,67.15) = 0.93$, $p = .438$, $\eta_p^2 = .04$.

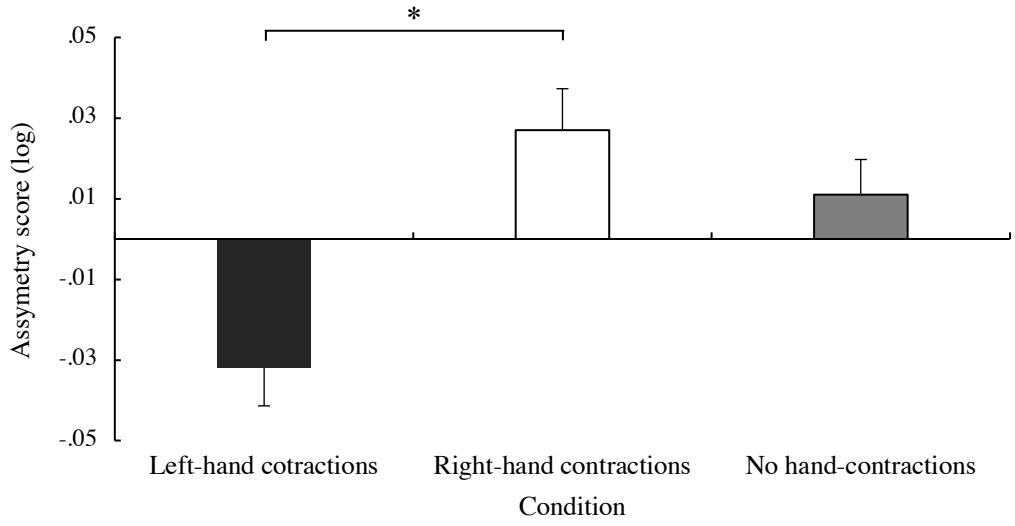

Figure 4.1 Alpha power asymmetry score for each condition. Asymmetry score was calculated by: right hemisphere – left hemisphere (positive values represent higher right-hemisphere power and negative values represent higher left-hemisphere power). Error bars represent standard error of the mean. * $p < .05$.

4.4.2 Cortical activity preceding golf putts

The results revealed a main effect of Condition, $F(2,48) = 122.5$, $p < .001$, $\eta_p^2 = .84$. Post-hoc analysis revealed that left-hand contractions led to significantly lower T7-Fz connectivity, than right-hand contractions ($p < .001$) or no hand-contractions (p

< .001, see Figure 4.2). Right-hand contractions revealed the opposite effect with significantly higher T7-Fz connectivity compared to left-hand contractions (p < .001) and no hand-contractions (p < .001, see Figure 4.2).

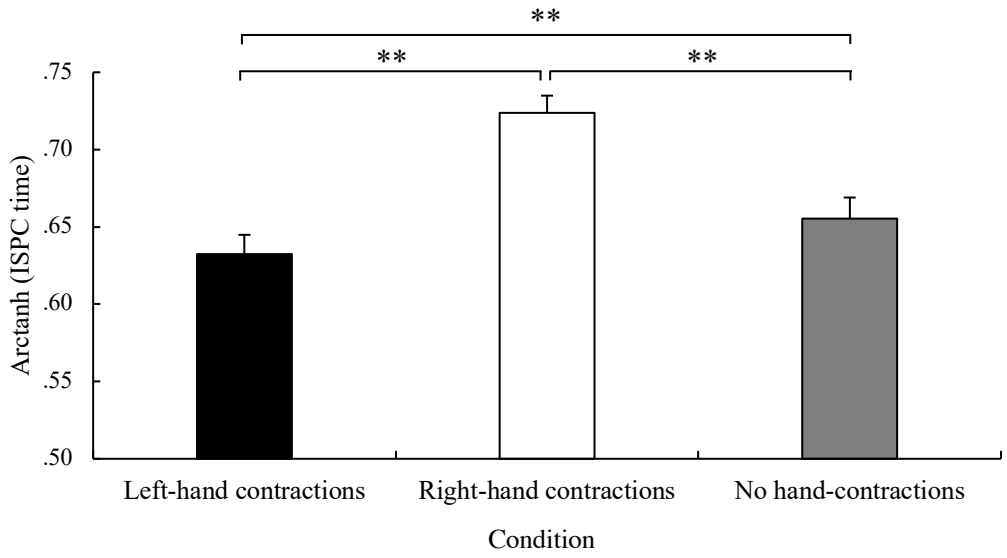

Figure 4.2 T7-Fz $ISPC_{time}$ connectivity for each condition. Error bars represent standard error of the mean. ** p < .001.

4.4.3 Muscle activity

No Condition x Time Bin interactions were evident for the extensor carpi radialis, $F(24,432) = 1.15$, $p = .290$, $\eta_p^2 = .06$, or the flexor carpi ulnaris, $F(24,480) = 0.82$, $p = .715$, $\eta_p^2 = .04$. A main effect of Time Bin was evident for the extensor carpi radialis, $F(3.73,67.11) = 9.99$, $p < .001$, $\eta_p^2 = .36$, and the flexor carpi ulnaris, $F(4.18,83.61) = 13.51$, $p < .001$, $\eta_p^2 = .40$. Post-hoc analysis revealed that for the extensor carpi radialis the variance for Time Bin was best described by a quadratic trend ($p < .001$, $\eta_p^2 = .53$), with a gradual increase of activity until peak in activity during movement initiation (time zero), which quickly drops back to baseline (see Figure 4.3). For the flexor carpi ulnaris, variance for Time Bin was also best described by a quadratic trend ($p < .001$, $\eta_p^2 = .68$), with similar trends to the extensor carpi radialis (see Figure 4.4). Main effects of Condition were not evident for the extensor carpi radialis, $F(2,36) = 1.74$, $p = .191$, $\eta_p^2 = .09$, or the flexor carpi ulnaris, $F(2,40) = 0.69$, $p = .510$, $\eta_p^2 = .03$.

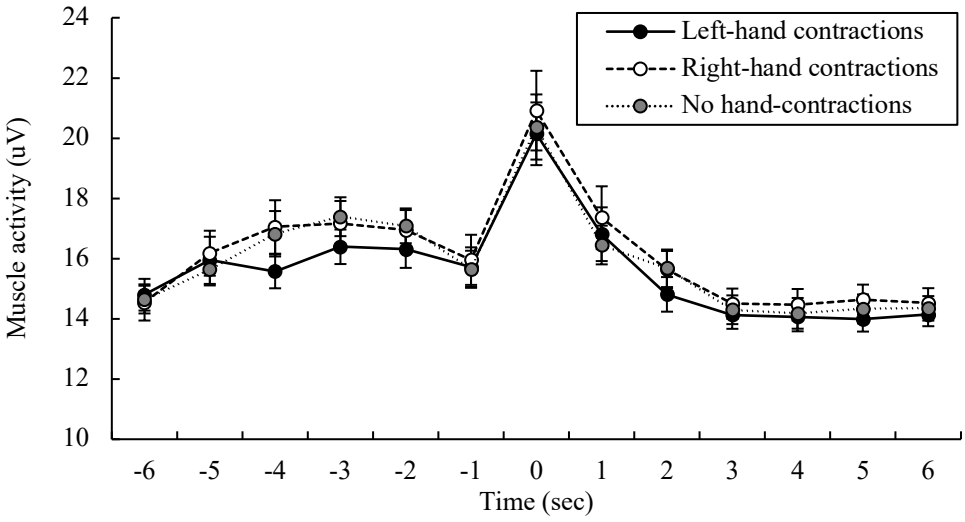

Figure 4.3 Activity of the extensor carpi radialis for each condition over time. Error bars represent standard error of the mean.

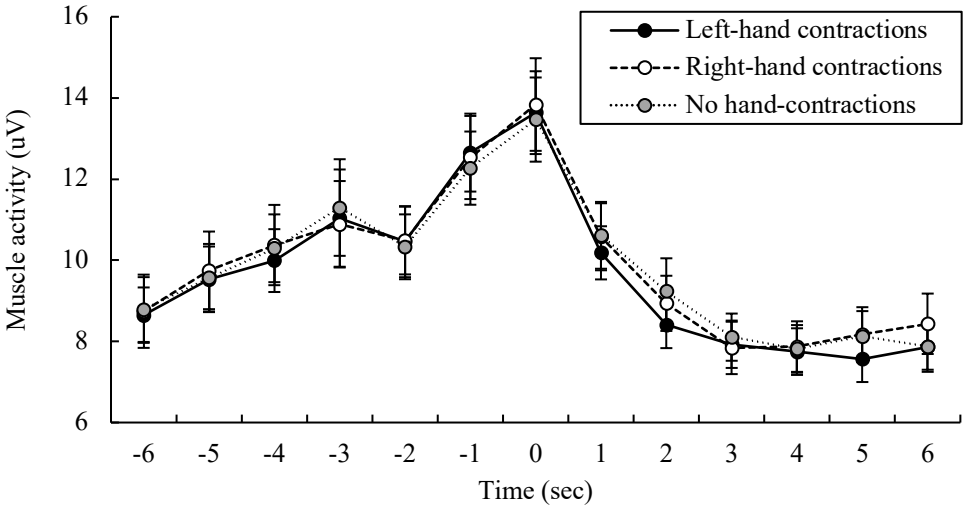

Figure 4.4 Activity for of the flexor carpi ulnaris for each condition over time. Error bars represent standard error of the mean.

4.4.4 Cardiac activity

The ECG analysis did not reveal a Condition x Time Bin interaction, $F(24,567) = 0.95$, $p = .532$, $\eta_p^2 = .04$, or a main effect of Condition, $F(2,48) = 0.62$, $p = .542$, $\eta_p^2 = .03$. A main effect of Time Bin was evident, $F(1.57,37.61) = 17.26$, $p < .001$, $\eta_p^2 = .42$. Post-hoc analysis revealed that heart rate differences over time was best described by a cubic trend ($p < .001$, $\eta_p^2 = .56$). Heart rate decreased during approximately 2 sec preceding movement initiation and then gradually retrurned to baseline in the 6 sec after movement initiation (see Figure 4.5).

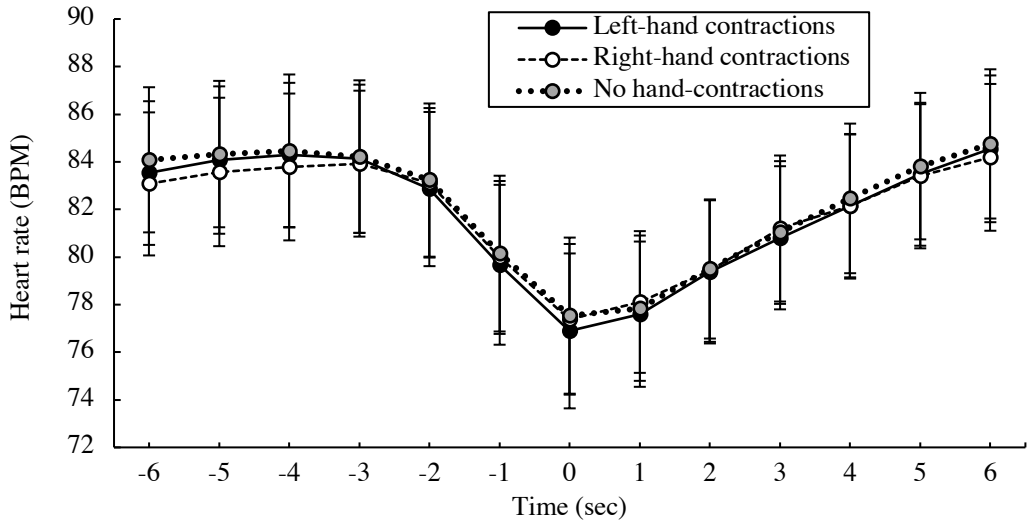

Figure 4.5 Heart rate for each condition over time (6 sec before until 6 sec after movement initiation). Error bars represent standard error of the mean.

4.4.5 Golf kinematics

No differences were evident between conditions for any of the kinematic measures: acceleration on the x-axis, $F(2,48) = 2.60$, $p = .085$, $\eta_p^2 = .10$; acceleration on the y-axis, $F(1.59,38.26) = 0.65$, $p = .493$, $\eta_p^2 = .03$; acceleration on the z-axis, $F(2,44) = 0.55$, $p = .581$, $\eta_p^2 = .02$; impact speed, $F(1.52,36.39) = 0.25$, $p = .718$, $\eta_p^2 = .01$; RMS jerk, $F(2,46) = 0.31$, $p = .738$, $\eta_p^2 = .01$; smoothness, $F(1.59,38.03) = 0.46$, $p = .592$, $\eta_p^2 = .02$.

4.4.6 Golf putting performance

No differences were evident between conditions for mean radial error, $F(2,48) = 1.75$, $p = .184$, $\eta_p^2 = .07$.

4.4.7 Mediation analysis

Mediation analyses were used to examine whether EEG, EMG, ECG or kinematics mediated the relationship between hand contractions and golf putting performance (mean radial error). Although there was no significant difference in performance between the different hand contraction conditions, there was a significant indirect effect of hand squeezing on performance via T7-Fz connectivity. Within-subject changes in performance following left-hand versus right-hand contractions were mediated by the changes in EEG T7-Fz connectivity induced by these protocols, B

= -12.41, BootSE= 4.12, 95% CI [-21.07, -4.94]. The other mediators did not reveal significant indirect effects on performance.

4.5 Discussion

The present study was conducted to examine whether pre-performance unilateral hand contraction protocols influence verbal-analytical engagement in motor performance. A repeated measures crossover design was adopted, measuring psychophysiological markers (neural, cardiovascular and muscular), performance (distance from the target) and movement kinematics of a golf putting task that was completed immediately after performing a hand contraction protocol (left-hand contractions, right-hand contractions and no hand-contractions). During the hand contraction protocols, measures of alpha power spectra between homologous electrode pairs were computed as a manipulation check to determine whether hand contractions caused different hemispheric activation.

The manipulation check revealed a significant difference in hemispheric asymmetry between left-hand and right-hand contraction protocols, with the left-hand contraction protocol resulting in more right-hemisphere activity and the right-hand contraction protocol resulting in higher left-hemisphere activity (see Figure. 4.1). These findings are consistent with previous studies (Gable et al., 2013; Harmon-Jones, 2006; Peterson et al., 2008).

Our study is the first to include a no hand-contractions, which makes it possible to compare the effect of left-hand and right-hand contractions relative to no contractions. Asymmetry during the no hand-contraction protocol was not significantly different from either contraction condition, which suggests that hand contractions did not create different asymmetry compared to no hand-contractions. However, hand contractions did achieve different asymmetry compared to each other. The slight rightward bias evident during the no hand-condition is in line with previous studies revealing that right-handedness is related to a bias to rightward hemisphere asymmetry (greater left-hemisphere activity) for resting state alpha power (e.g., Ocklenburg et al., 2019).

As hypothesized, a lower level of T7-Fz connectivity during preparation for putts was revealed after left-hand contractions, compared to right-hand contractions and no hand-contractions. The opposite effect was found for right-hand contractions,

revealing higher T7-Fz connectivity compared to left-hand contractions and no hand-contractions. Previous studies have suggested that lower T7-Fz connectivity reflects less verbal-analytical engagement in movements (e.g., Deeny et al., 2003; Gallicchio et al., 2016; Zhu, Poolton, Wilson, Maxwell, et al., 2011). Left-hand contractions in the present study may therefore have lowered T7-Fz connectivity and reduced verbal-analytical engagement in the putting task, compared to right-hand and no hand-contractions.

Although there was no significant effect of hand contractions on golf putting performance,[31] mediation analysis suggested that hand contractions influenced T7-Fz connectivity, which in turn influenced performance. Beckmann et al. (2013) and Gröpel and Beckmann (2017) speculated that top-down verbal-analytical control processes are the mechanism by which hand contractions influence performance under pressure. Many explanations of skill failure, such as the theory of reinvestment (Masters, 1992; see Masters & Maxwell, 2008, for a review), suggest that attempts to consciously control movements (characterised by verbal-analytical processing), can disrupt normally efficient motor behaviours. Given the hypothesised link between T7-Fz connectivity and conscious verbal engagement of movement, our mediation findings provide some support for their speculation.

Although the hand contraction protocols clearly influenced neurophysiological activity, their effects did not extend to the cardiac, muscular or kinematic measures. There were no condition effects for these variables and there were no mediational effects to implicate any of these variables in the relationship between hand contractions and performance. From a theoretical perspective it makes sense that neural measures should be more sensitive to the effects of hand contraction protocols than peripheral measures such as heart rate, because verbal-analytic processes originate from the brain, and any effects they might have on the heart and muscles would always be secondary. Any effects of psychological processes on cardiac and muscular activity could also have been masked by any physical strain on these variables caused by the golf putting task (e.g., standing posture, swinging arms, etc.).

[31] It is acceptable to conduct mediation analysis when there is no significant effect of the independent variable (hand contractions) on the dependent variable (golf putting performance) (see e.g., Kenny, Kashy, & Bolger, 1998).

Despite the indirect effect of hand contractions on performance through T7-Fz connectivity, there were no significant performance differences between the different hand contraction protocols. Our participants only performed 130 trials prior to the first hand contraction condition, so they remained relatively inexperienced novices with high inter and intra person performance variability that may have camouflaged any subtle (direct) hand contraction effects. A more cognitively challenging task may reveal performance differences. Zhu et al (2015) also manipulated T7-Fz coherence, using real versus sham tDCS, and also failed to find an effect on golf putting performance alone. *However, Zhu et al. (2015) did report a differential effect on golf putting performance under dual-task load (e.g., backwards counting).* Alternatively, replicating the experiment with more experienced performers could also increase the likelihood of performance differences. For example, the theory of reinvestment (Masters & Maxwell, 2008) argues that verbal-analytic engagement (e.g., right-hand contractions) would be more detrimental to the performance of autonomous experts than cognitive novices. Effects of condition on the cardiac, muscular and kinematic measures would also be more likely with experienced performers for the same reasons.

A limitation of this study is that we did not control force of grip used by participants during the hand contraction protocol. Consequently, differences in hemisphere asymmetry might have been a function of effort or strength. For example, Hirao and Masaki (2018) showed that force and duration of left-hand contractions had differential effects on hemisphere activity. Additionally, a requirement to achieve a specific force during contractions may require more cognitive resources (e.g., Derosière et al., 2014; Hirao & Masaki, 2018). One solution might simply be to measure grip force and include it as a covariate in analysis of hemisphere asymmetry. This issue should be addressed in further studies.

Another limitation is that we were unable to determine the longevity of the hand contractions with respect to their effect on cortical activity. Studies suggest that the effects of hand contraction protocols last at least 15 min (e.g., Baumer, Munchau, Weiller, & Liepert, 2002). Participants in our study completed 25 trials over approximately a 6 min duration, so it is likely that the effects remained. However, there is little doubt that further research is needed to gain greater understanding of the timecourse of hand contraction effects.

To our knowledge this is the first study reporting neural evidence that left-hand contractions lower verbal-analytical engagement in motor planning of a golf putting task. The additional markers (ECG, EMG, kinematics and performance) did not, however, provide supporting evidence of this effect. These secondary markers may have been insufficiently sensitive to reveal the brain's influence over the body. Nevertheless, it appears that the body (the hands) influenced the brain!

Chapter 5

Experiment 4: The effects of unilateral hand contractions on verbal-analytical engagement during early motor learning[32]

5.1 Abstract

The findings of Experiment 3 suggested that pre-performance left-hand contractions reduced verbal-analytical engagement during motor planning, whereas pre-performance right-hand contractions increased verbal-analytical engagement during motor planning. Consequently, hand contractions might be useful for increasing or reducing conscious processes, such as hypothesis testing, during motor learning. Experiment 4, therefore, examined whether pre-performance left-hand contractions promote implicit motor learning, and whether pre-performance right-hand contractions promote explicit motor learning. Forty-eight golf-novices were randomly allocated to left-hand contractions, right-hand contractions or no hand-contractions (control) groups. A line bisection task was conducted as a manipulation check of whether hemisphere asymmetry occurred. All participants practiced a golf putting task, with their allotted hand contraction protocol performed for 30 sec before every ten putts. Thereafter, participants completed two retention tests (blocks of single-task putting) before and after one transfer test (a block of dual-task putting). Different objective and subjective measures of verbal-analytical engagement were collected. Golf putting accuracy and kinematics were assessed. Additionally, mood-state as a function of hemisphere asymmetry was measured. The line bisection task did not reveal a hemisphere asymmetry effect of the different hand contraction protocols. All groups equally improved during practice; however, the no hand-contractions (control) group showed better performance during both retention tests compared to left-hand and right-hand contractions groups. All groups performed worse in the dual-task transfer test. The objective and subjective

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[32] Based on: **Hoskens, M. C. J.,** Uiga, L., Cooke, A., Capio, C. M., & Masters, R. S. W. (under review). The effects of unilateral hand contractions on conscious control in early motor learning, *Journal of Sport and Exercise Science (Special Issue, Skill Acquisition: Research & Practice).*

measures of verbal-analytical engagement revealed no effect of hand contractions. General mood-state decreased for all groups from pre- to post-practice. Unilateral hand contractions prior to practicing the golf-putting task did not affect performance differently from the no hand-contractions (control) group. However, hand contractions resulted in worse performance compared to the no hand-contractions group during the retention tests, and dual-task transfer performance disrupted performance in all groups. No differences in verbal-analytical engagement were evident. Consequently, left-hand contractions did not promote implicit motor learning. Possible explanations and recommendations for future studies are discussed.

5.2 Introduction

Pre-performance unilateral hand contraction protocols have been revealed to cause hemispheric asymmetry (Gable et al., 2013; Harmon-Jones, 2006; Peterson et al., 2008; Schiff et al., 1998). Contralateral couplings between the hands and the brain mean that left-hand contractions activate the right hemisphere and suppress the left hemisphere, whereas right-hand contractions activate the left hemisphere and suppress the right hemisphere. Beckmann et al. (2013) and Gröpel and Beckmann (2017) showed that left-hand contractions prior to skill execution led to better motor performance under pressure compared to right-hand contractions among semi-professional athletes. The left hemisphere of the brain is known to be responsible for verbal-analytical processes, whereas the right hemisphere is responsible for visual-spatial processes (De Renzi, 1982), so Beckmann et al. (2013) suggested that better performance under pressure was a consequence of left-hand contractions suppressing the left hemisphere and thus suppressing disruptive verbal-analytical processes. Verbal-analytical processes have been linked to conscious control of movement (e.g., Gallicchio et al., 2016; Zhu, Poolton, Wilson, Maxwell, et al., 2011), which is associated with disrupted motor performance under pressure (e.g., Masters & Maxwell, 2008; Zhu, Poolton, Wilson, Maxwell, et al., 2011).

Hoskens, Bellomo, Uiga, Cooke, and Masters (2020, Chapter 4) were the first to use cortical activity to investigate whether pre-performance unilateral hand contraction protocols influenced verbal-analytical engagement in motor planning during a golf putting task. Verbal-analytical engagement in motor planning is

thought to influence cortical synchronization (i.e., EEG connectivity) between the verbal left temporal (T7) and the motor planning mid-frontal (Fz) locations on the scalp in the final seconds before and during movements (e.g., Gallicchio et al., 2016; Zhu, Poolton, Wilson, Maxwell, et al., 2011). Hoskens et al. (2020, Chapter 4) revealed that pre-performance left-hand contractions resulted in lower T7-Fz connectivity during performance of a golf putting task compared to right-hand and no hand-contraction protocols, and this was interpreted to indicate reduced verbal-analytical engagement in motor planning during performance. Furthermore, pre-performance right-hand contractions caused increased T7-Fz connectivity, which may indicate greater verbal-analytical engagement compared to left-hand contractions or no hand-contractions.

Based on the findings of Hoskens et al. (2020, Chapter 4), this study examined whether left-hand contraction protocols have potential to cause implicit motor learning by reducing verbal-analytical engagement during motor planning. In contrast to explicit motor learning, implicit motor learning is designed to minimizes verbal-analytical processes during movement planning and execution by specifically reducing the amount of verbal-analytical knowledge that a performer can access explicitly (e.g., Masters, 1992; Masters & Maxwell, 2004; Maxwell, Masters, & Eves, 2003). It has been claimed that implicit processes are more efficient at guiding movements and result in robust performance under pressure compared to explicit processes (Masters, 1992; Masters et al., 2019). Different approaches have been established to promote implicit motor learning. Masters (1992) asked people practicing a golf putting task to also carry out a secondary task (continuously generating random letters of the alphabet in time with a metronome). The secondary task used up resources normally available to process information about the putting task, so participants learned implicitly. Maxwell et al. (2001) reduced the amount of errors during golf putting practice by starting from close to the target and then gradually moving further away in increments of 25cm. Maxwell et al. (2001) found that reducing the amount of errors during practice lowered the likelihood that participants would use verbal-analytical processes to consciously improve their performance, presumably because they were successful. Zhu et al. (2015) used cathodal (i.e., inhibitory) transcranial direct current stimulation (tDCS) to reduce activity in the left dorsolateral prefrontal cortex (DLPFC), which is

associated with working memory processes and verbal learning mechanisms (Brunoni & Vanderhasselt, 2014). Zhu et al. (2015) found evidence of suppressed verbal-analytical engagement during movement planning and execution, reflective of implicit motor learning.

Here we examine whether a pre-performance left-hand contraction protocol can be used to promote implicit motor learning by suppressing verbal-analytical engagement in the task and thereby minimizing accumulation of explicit knowledge. Three groups of participants practiced a golf putting task. Prior to each block of trials, participants completed left-hand contractions, right-hand contractions or no hand-contractions. Similarly to Goldstein, Revivo, Kreitler, and Metuki (2010), a line bisection task was used as a manipulation check of whether hand contractions caused hemispheric asymmetry.[33] After a recovery interval they completed a test phase, which consisted of two retention tests separated by a dual-task transfer test. The retention tests were used to establish effects on performance (mean radial error) after boredom and fatigue had abated. The dual-task transfer test was used as an indicator of implicit motor learning. Explicitly learned motor tasks are typically disrupted by a secondary task that requires verbal-analytical processing, because performance of the motor task also requires verbal-analytical processing. Implicitly learned motor tasks, on the other hand, are not disrupted by a secondary task that requires verbal-analytical processing, because performance of the motor task does not require verbal-analytical processing (e.g., Maxwell, et al., 2001). Subjective and objective measures of technique change during practice were also used to assess whether hand contraction protocols influenced verbal-analytical engagement in performance. Changes in technique are associated with verbal-analytical engagement in performance as people search for motor solutions (Maxwell et al., 2001; Maxwell et al., 2006). Additionally, following the first retention test, participants were asked to recall the final position of the ball on each trial. We

[33] In most people, attention is spatially biased to the left, which causes them to judge the centre of a horizontal line to be more to the left than the right (for a review see, Jewell & McCourt, 2000). This phenomenon, *pseudoneglect* (Bowers & Heilman, 1980), is thought to occur because the right hemisphere of the human brain is dominant for spatial attention processes (e.g., Roberts & Turnbull, 2010; Turner, Hahn, & Kellogg, 2017) and is strongly connected with the contralateral hemispace (e.g., Corbetta, Miezin, Shulman, & Petersen, 1993). If hand contraction protocols influence hemisphere activity they should influence spatial bias. Goldstein et al. (2010), for example, revealed that left-hand contraction protocols resulted in greater bias to the left in the line bisection task, whereas right-hand contractions resulted in greater bias to the right.

speculated that participants would have better recall if they had been using verbal-analytical processes to consciously test hypotheses based on the outcomes of putts on previous trials.

Finally, measures of general and motor related mood-states were assessed prior to and after golf putting practice to control for conflicting mood states that may have been caused by the hand contraction protocols.[34]

Our primary interest was in the effects of hand contractions on motor learning. We predicted that left-hand contractions, which raise activity in the right hemisphere and lower activity in the left hemisphere, would reduce verbal-analytical engagement in movements during practice of a golf putting task, promoting implicit motor learning. We therefore expected left-hand contractions to result in fewer self-reported technique changes, lower kinematic variability in technique, worse recall of performance outcome and better performance on a dual-task transfer test compared to right-hand and no hand-contractions. Additionally, in line with the valance hypothesis, we also expected that the hand contractions would influence mood, with right-hand contractions prompting more positive states and left-hand contractions prompting more negative states during motor performance.

5.3 Method

5.3.1 Participants

Forty-eight people were recruited to participate in this study (mean age = 24.46 years, SD = 5.85 years, 26 female). All participants had normal/corrected vision and self-reported being right-hand dominant. A between subjects design was adopted, with the participants randomly allocated to a left-hand contractions, right-hand contractions or no hand-contractions (control) group. Participants completed a practice phase followed by a test phase (see Procedure). The study received ethical approval from the University Human Research Ethics Committee.

[34] The '*valence hypothesis*' suggests that the left hemisphere is associated with positive emotions, whereas the right hemisphere is associated with negative emotions (see Davidson, 1992, for a review). Consistent with the 'valence hypothesis', evidence suggests that right-hand contractions promote more positive emotions (i.e., higher left hemisphere activity) but left-hand contractions promote more negative emotions (Propper, Dodd, Christman, & Brunye, 2017; Schiff & Lamon, 1994; Schiff & Truchon, 1993).

5.3.2 Tasks

The hand contraction protocols required participants to firmly contract a stress ball at a self-paced rate either with their left hand or right hand. In the no hand-contraction (control) group, participants placed their hands in their lap and held them still.

The golf putting task consisted of hitting a regular-size golf ball (4.7 cm diam.) to a target on an artificial grass surface, using a golf putter (80 cm length) (see Figure 5.1.A). The target (a 12 cm diam. black circle) was positioned 1.9 m from the starting position. We used a flat target instead of the traditional golf putting hole in order to yield precise measures of performance, in terms of both accuracy (i.e., mean radial error) and directional bias (i.e., directional error) (see Figure 5.1.B). The SAM PuttLab system (SAM PuttLab, Science motion GmbH, Munich, Germany, www.scienceandmotion.de), with an overall sampling rate of 210 Hz, was used to obtain kinematics of the putter (*SAM PuttLab reports manual*, 2010).

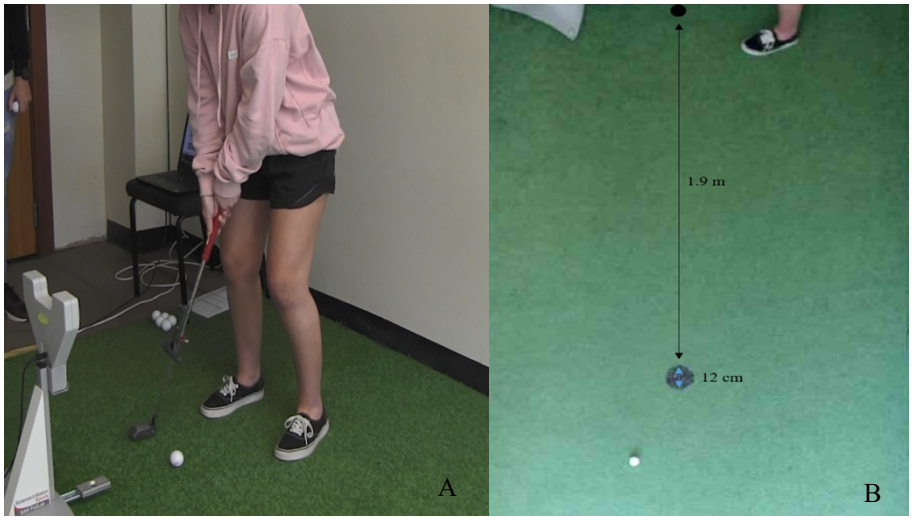

Figure 5.1 Experimental set up of the golf putting task. A) SAM PuttLab set up B) dimensions of the target.

5.3.3 Measures

5.3.3.1 Line bisection - manipulation check

The line bisection task was conducted prior to and after a single pre-practice hand contraction protocol before motor practice, and once after motor practice, to confirm whether hand contractions influenced hemispheric asymmetry, which

would result in greater leftward bias for left-hand contractions and greater rightward bias for right-hand contractions (e.g., Goldstein et al., 2010; Jewell & McCourt, 2000).

The line bisection task required participants to mark the exact middle of two straight horizontal lines (18 cm length) presented consecutively on a sheet of paper. The lines were offset either to the left or to the right on the sheet of paper (Goldstein et al., 2010). Deviation from the middle point of the line (i.e., 9 cm) was calculated as percentage bias error (Scarisbrick, Tweedy, & Kuslansky, 1987). The mean percentage bias error of the two trials was computed. Positive scores reflect prejudice to mark further to the right side of the line, suggesting increased left hemisphere activation, whereas negative scores reflect prejudice to mark further to the left side suggesting increased right hemisphere activation (Goldstein et al., 2010).

5.3.3.2 Measures of verbal-analytical engagement in the putting task

Self-reported technique changes. Following the practice phase, participants answered questions related to technique changes (i.e., '*I tried different ways of hitting the target'* and *'I changed my technique while doing the golf-putting task'*). The items were rated on a 6-point Likert Scale ranging from 1 (*strongly disagree*) to 6 (*strongly agree*). The mean score of both questions was taken.

Kinematics. Golf putting swing kinematics were computed to provide insight into technique changes during practice and testing (e.g., Maxwell et al., 2003). The kinematics obtained from the SAM PuttLab data were standard deviation (SD) of the putter velocity at impact (mm/sec) and putter face angle at impact (degrees) (see Malhotra et al., 2015).

Performance outcome recall. Following the first retention test, participants were asked to recall the general dispersion of their putts by indicating the number of putts that had come to rest in each area of a diagrammatic representation of the target area (see Figure 5.2). Recall performance was calculated as the absolute difference between the reported numbers and the actual number of balls in each area.

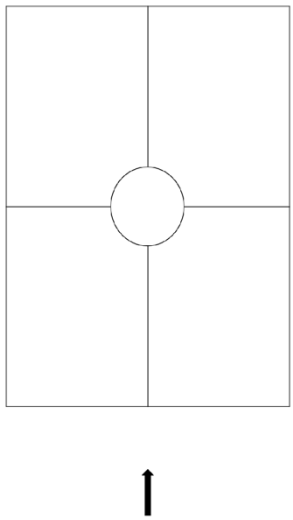

Figure 5.2 Recall sheet.

Golf performance measures. Two performance scores – radial error (cm) and directional error (cm) – were computed for each golf putt, using *ScorePutting* software (written in National Instruments LabVIEW), which uses photographs from a camera placed directly above the putting target (Neumann & Thomas, 2008).

Radial error represents the distance between the final position of the golf ball and the centre of the target (i.e., lower error represents better performance). Directional error represents the perpendicular distance (left or right) between the final position of the golf ball and a straight line from the starting point to the centre of the target. Negative values were assigned to leftward errors and positive values were assigned to rightward errors.

5.3.3.3 Mood-state

Overall mood-state was measured prior to and after golf putting practice, using one question (i.e., '*overall, my mood at the moment is*'), which was rated on a Likert-type scale ranging from -10 (*very unpleasant*) to 10 (*very pleasant*).

Mood-state associated with the golf putting task was measured after practice, using four questions addressing anger (i.e., '*I got angry with myself when I did not perform well*'), frustration (i.e., '*I found the golf-putting task frustrating*'), irritation (i.e., *'I found the golf-putting task irritating'*), and boredom (i.e., *'I got bored during the golf-putting task'*). The items were rated on a 6-point Likert-type scale ranging from 1 (*strongly disagree*) to 6 (*strongly agree*).

5.3.4 Procedure

Participants were informed about the context of the study, signed an informed consent form and completed the demographics and overall mood-state questionnaires prior to the start of the experiment. They then completed the line bisection task before and after performing a single hand contraction protocol for 45 sec (left-hand, right-hand or no hand-contractions). After this, seven blocks of ten golf putting trials were completed, with each block preceded by a 30 sec hand contraction protocol (left-hand, right-hand or no hand-contractions).[35] Upon completion of the 70 trials, participants again completed the line bisection task. The self-report measures of technique changes, and of overall mood-state as well as mood-state associated with the golf putting, were also administered. Finally, following a rest interval (10 min), a test phase was performed. The test phase consisted of a dual-task transfer test (10 trials of putting and tone counting) sandwiched between two retention tests (10 trials of single-task putting each). During the dual-task transfer test, participants heard low (500 Hz) and high (1000 Hz) pitched tones (interval 1000 msec) played through computer software (Labview Application Builder 2010, National Instruments Inc., Austin, TX) in a randomized order. Participants were asked to count the number of low pitched tones. The absolute deviation between number of tones reported and the number of tones presented was calculated as a performance percentage. After completion of retention test 1, participants were asked to recall the final resting position of each of their putts.

5.3.5 Statistical approach

Percentage bias error (i.e., deviation left or right of exact middle, cm) during the line bisection tasks was subjected to a 3 x 3 repeated measures analysis of variance (ANOVA): Group (Left-hand contractions, Right-hand contractions, No hand-contractions) x Test (Pre-practice test 1, Pre-practice test 2, Post-practice test). To determine whether pseudoneglect occurred, we conducted one-sample t tests (critical value 0.00 cm deviation, i.e., exact middle of the line).

[35] We used multiple hand contraction protocols to maintain the effects of the hand contraction protocols on brain activity.

Self-reported technique changes and performance outcome recall scores were analysed by one-way ANOVA: Group (Left-hand contractions, Right-hand contractions, No hand-contractions). For the practice phase, the SAM PuttLab measures (SD face impact and velocity impact), radial error and directional error were subjected to a 3 x 7 repeated measures ANOVA: Group (Left-hand contractions, Right-hand contractions, No hand-contractions) x Block (B1, B2, B3, B4, B5, B6, B7). For the test phase, the SAM PuttLab measures, radial error and directional error were subjected to a 3 x 3 repeated measures ANOVA: Group (Left-hand contractions, Right-hand contractions, No hand-contractions) x Test (Retention 1, Dual-task transfer, Retention 2). Tone counting performance during the dual-task transfer test was subjected to a one-way ANOVA: Group (Left-hand contractions, Right-hand contractions, No hand-contractions).

Overall mood-state was subjected to a 3 x 2 repeated measures ANOVA: Group (Left-hand contractions, Right-hand contractions, No hand-contractions) x Test (Pre-practice phase, Post-practice phase). The motor task-specific mood-state questions were subjected to a one-way ANOVA: Group (Left-hand contractions, Right-hand contractions, No hand-contractions).

Sphericity and normality checks were performed and controlled for when needed. When main effects or interactions were found, separate ANOVAs, post-hoc tests (Bonferroni corrected) or polynomial trend analyses were performed. Effect sizes are reported as partial η squared (η_p^2), with the values .01, .06 and .14 indicating relatively small, medium and large effect sizes, respectively (Cohen, 1988). The Cohen's d effect size is reported for the independent t-test, with the values .2, .5 and .8 indicating relatively small, medium and large effect sizes, respectively (Cohen, 1988). The statistical tests were performed using SPSS (IBM, version 26.0) computer software. Significance was set at $p = .05$ for all statistical tests.

5.4 Results

5.4.1 Manipulation check

5.4.1.1 Line bisection – manipulation check

No main effects of Group, $F(2,45) = 0.04$, $p = .958$, $\eta p^2 < .01$, or Test, $F(2,90) = 0.66$, $p = .520$, $\eta p^2 = .01$, were revealed for percentage bias error. There was also no Group x Test interaction, $F(4,90) = 0.44$, $p = .777$, $\eta p^2 = .02$ (see Table 5.1).

Given that there were no Group or Test effects and no Group x Test interaction, we collapsed all bias errors together (mean deviation = -0.54 cm, SD = 2.39) and conducted a single one-sample *t* test (critical value 0.00 cm; exact middle of line) to establish whether spatial bias was evident. A significant difference from 0.00 cm was not evident, $t(48) = -1.55$, $p = .127$, $d = .22$.

Table 5.1 Mean and SD percentage bias error in each group by line bisection test.

Group	Left-hand contractions		Right-hand contractions		No hand-contractions	
	M	SD	M	SD	M	SD
Pre-practice test 1 (%)	-0.09	3.72	-0.16	2.28	-0.87	3.39
Pre-practice test 2 (%)	-0.73	4.06	-0.02	3.13	-0.38	3.34
Post-practice test (%)	-0.68	3.34	-1.13	2.25	-0.78	2.12

Note. A negative mean value means a more leftward bias, and positive value a more rightward bias.

5.4.2 Measures of verbal-analytical engagement

5.4.2.1 Self-reported technique changes

The mean score on the self-report technique change questions was 4.34 (SD = 1.06) for the left-hand contraction group, 4.22 (SD = 1.09) for the right-hand contraction group and 4.53 (SD = 1.09) for the no hand-contraction group. No main effect of Group was evident, $F(2,47) = 0.34$, $p = .714$, $\eta p^2 = .02$.

5.4.2.2 Kinematics

Practice phase. The SD of velocity at impact revealed a main effect of Block, $F(4.66,139.64) = 19.50$, $p < .001$, $\eta p^2 = .39$, but no main effect of Group, $F(2,30) = 0.77$, $p = .474$, $\eta p^2 = .05$, or Group x Block interaction, $F(12,180) = 0.26$, $p = .994$, $\eta p^2 = .02$ (see Figure 5.3). Post-hoc analysis of the Block effect revealed a quadratic trend, ($p < .001$, $\eta p^2 = .63$); SD of velocity at impact decreased sharply over the first blocks of trials and then levelled off.

The SD of face angle at impact revealed a main effect of Block, $F(6,180) = 4.11$, $p = .001$, $\eta p^2 = .12$, but no main effect of Group, $F(2,30) = 0.45$, $p = .643$, $\eta p^2 = .03$, or Group x Block interaction, $F(12,180) = 0.66$, $p = .785$, $\eta p^2 = .04$ (see Figure 5.4). Post-hoc analysis of the Block effect revealed a linear trend ($p < .001$, $\eta p^2 = .44$); SD of face angle at impact reduced gradually across blocks of trials.

Test phase. SD of velocity at impact did not reveal a significant main effect of Group, $F(2,37) = 2.40$, $p = .105$, $\eta p^2 = .12$, or of Block, $F(1.73,63.93) = 1.16$, $p = .314$, $\eta p^2 = .03$. There was no Group x Block interaction effect, $F(4,74) = 0.15$, $p = .964$, $\eta p^2 = .01$ (see Figure 5.3).

SD of face angle at impact did not reveal a significant main effect of Group, $F(2,37) = 0.45$, $p = .643$, $\eta p^2 = .02$, or of Block, $F(2,74) = 1.69$, $p = .191$, $\eta p^2 = .04$, and there was no Group x Block interaction effect, $F(4,74) = 0.58$, $p = .677$, $\eta p^2 = .03$ (see Figure 5.4).

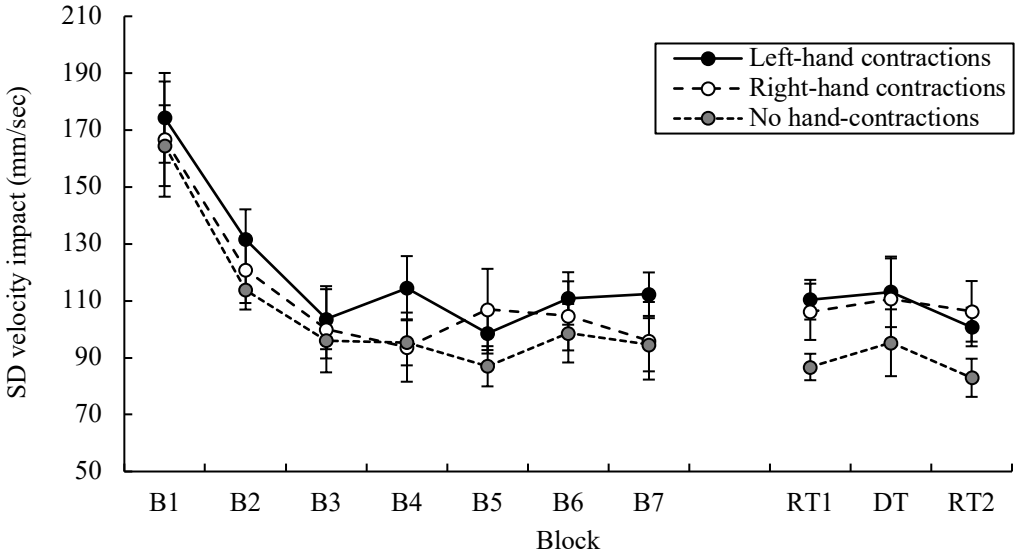

Figure 5.3 SD of velocity at impact for each block of trials during the practice and test phases, as a function of hand contraction protocol. Error bars represent the standard error of the mean.

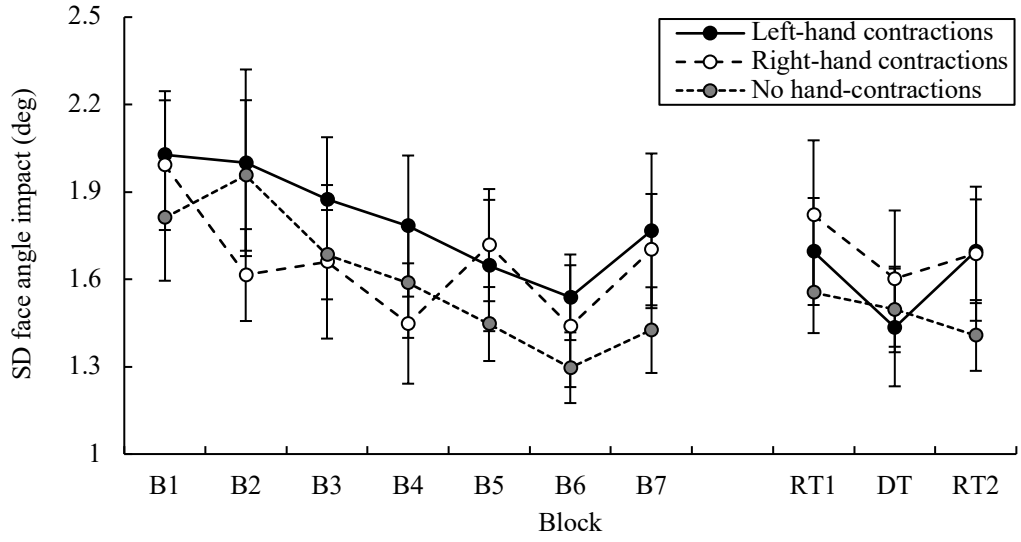

Figure 5.4 SD of face angle at impact for each block of trials during the practice and test phases, as a function of hand contraction protocol. Error bars represent the standard error of the mean.

5.4.2.3 Performance outcome recall

Mean recall accuracy was calculated as the number of correctly recalled final ball positions out of the ten trials of retention test 1. Mean recall accuracy was 4.63 (SD = 2.80) for the left-hand contraction group, 5.5 (SD = 1.71) for the right-hand

contraction group, and 5.38 for the no hand-contraction (control) group. No main effect of Group was found, $F(2,47) = 0.46$, $p = .635$, $\eta p^2 = .02$.

5.4.2.4 Golf putting performance

Practice phase. For radial error, a main effect of Block was revealed, $F(6,246) = 28.06$, $p < .001$, $\eta p^2 = .41$, but there was no main effect of Group, $F(2,41) = 1.01$, $p = .375$, $\eta p^2 = .05$, and a Group x Block interaction was not evident, $F(12,246) = 0.63$, $p = .817$, $\eta p^2 = .03$ (see Figure 5.5). Post-hoc analysis of the Block effect revealed a linear trend ($p < .001$, $\eta p^2 = .76$), suggesting that constant incremental reductions in radial error occurred across blocks of trials.

For directional error, main effects were not evident for Group, $F(2,41) = 0.26$, $p = .771$, $\eta p^2 = .01$, or for Block, $F(6,246) = 1.04$, $p = .399$, $\eta p^2 = .03$, and a Group x Block interaction was not evident, $F(12,246) = 0.99$, $p = .450$, $\eta p^2 = .05$ (see Figure 5.6).

Test phase. For radial error, main effects were evident for Group, $F(2,41) = 4.92$, $p = .012$, $\eta p^2 = .19$, and Block, $F(1.77,72.51) = 15.10$, $p < .001$, $\eta p^2 = .27$. However, there was not a Group x Block interaction, $F(4,82) = 1.99$, $p = .104$, $\eta p^2 = .09$ (see Figure 5.5). Post-hoc analysis of the Group effect revealed significantly lower radial error in the no hand-contraction group compared to both the right-hand contraction group ($p = .020$) and the left-hand contraction group ($p = .047$). Radial error did not differ between the left-hand contraction and right-hand contraction groups ($p = 1.00$). Post-hoc analysis of the Block effect revealed significantly greater radial error during the dual-task transfer test, compared to retention test 1 ($p = .001$) and retention test 2 ($p < .001$). Radial error did not differ in the two retention tests ($p = 1.00$).

For directional error, no main effects were evident for Group, $F(2,41) = 0.51$, $p = .605$, $\eta p^2 = .02$, and Block, $F(2,84) = 2.92$, $p = .059$, $\eta p^2 = .07$. There was also no Group x Block interaction, $F(4,82) = 0.43$, $p = .783$, $\eta p^2 = .02$ (see Figure 5.6).

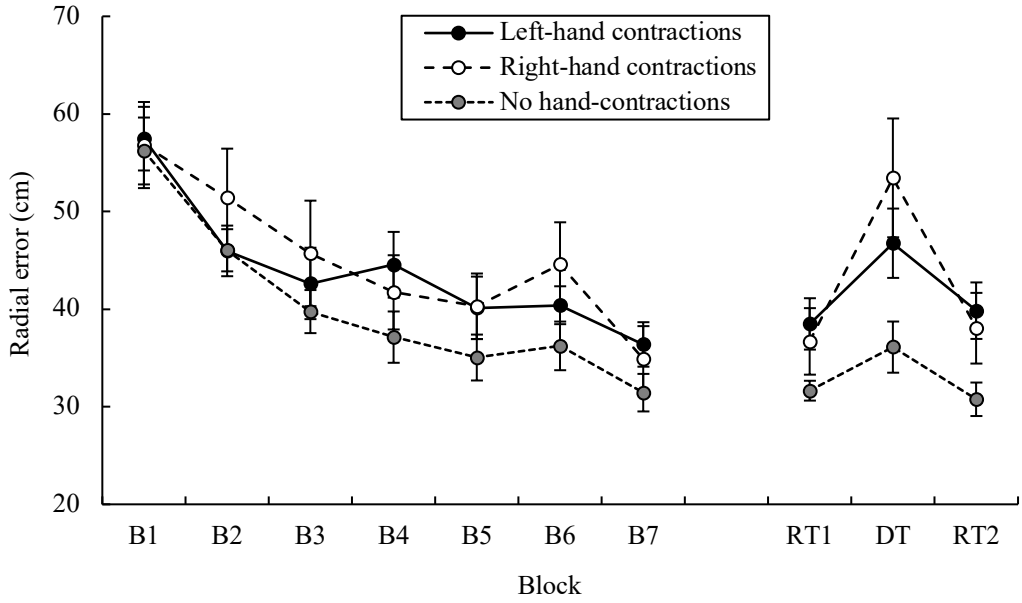

Figure 5.5 Radial error for each block of trials in the practice phase and the test phase, as a function of hand contraction protocol. Error bars represent the standard error of the mean.

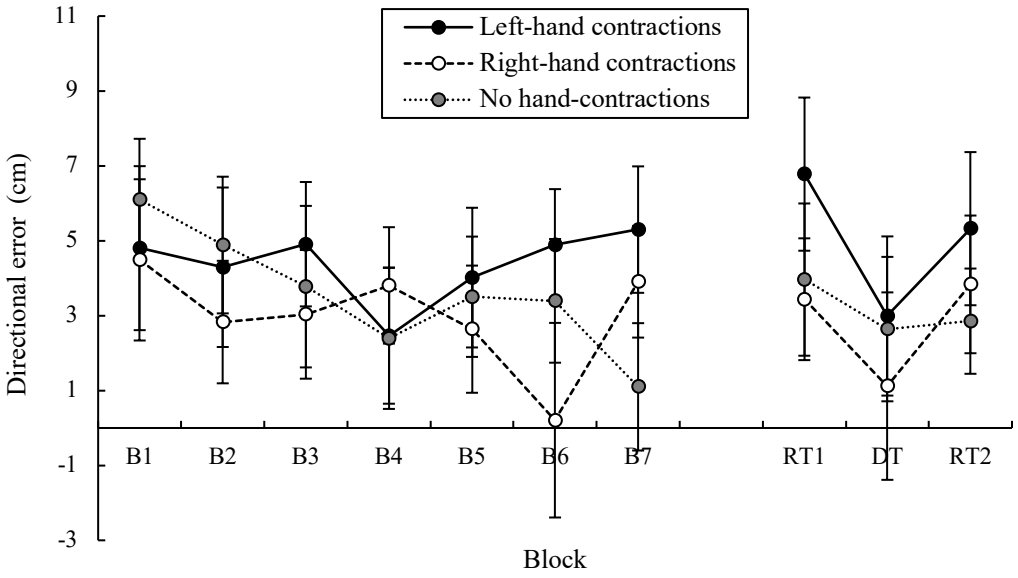

Figure 5.6 Directional error for each block of trials in the practice phase and the test phase, as a function of hand contraction protocol. Error bars represent the standard error of the mean.

5.4.2.5 Tone counting accuracy

Mean tone counting accuracy was 92% (SD = 0.08%) for the left-hand contraction group, 92% (SD = 0.09%) for the right-hand contraction group and 93% (SD = 0.06%) for the no hand-contraction (control) group. There was no significant

difference in tone counting accuracy between groups, F(2,45) = 0.19, p = .828, ηp^2 = .01.

5.4.3 Mood-state

For overall mood-state, there were significant main effects of Group, F(2,45) = 3.93, p = .027, ηp^2 = .15, and Test, F(1,45) = 9.53, p = .003, ηp^2 = .18 (see Figure 5.7). A Group x Test interaction was not evident, F(2,45) = 0.14, p = .872, ηp^2 = .01 was revealed. Post-hoc analysis of the Group effect revealed that overall the left-hand contraction group reported significantly lower mood compared to the no hand-contraction control group (p = .023), but the right-hand contraction group did not differ from either of the other groups (p's > .39). Significantly lower mood was evident after the practice phase compared to before the practice phase for all groups.

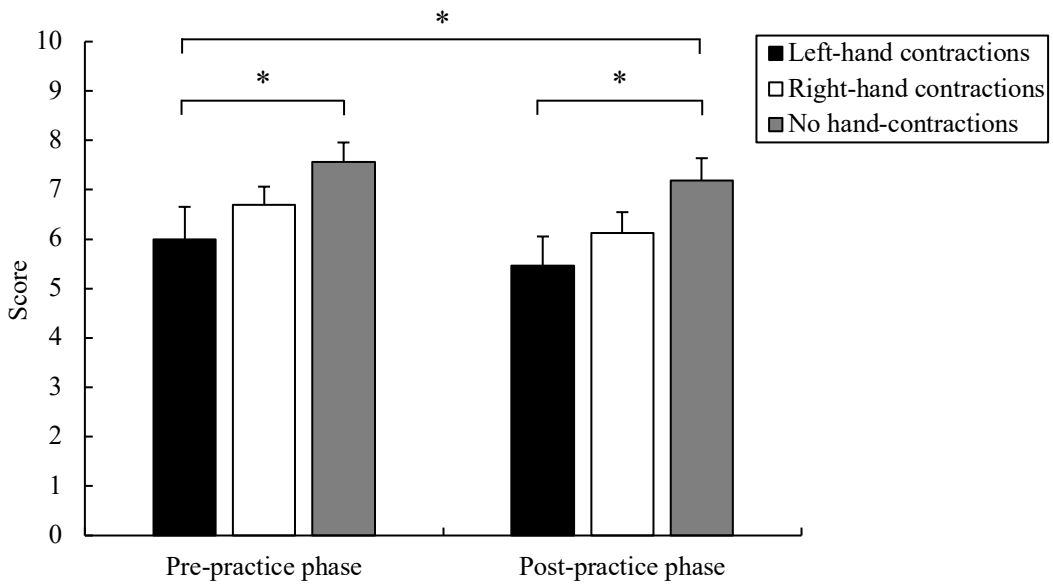

Figure 5.7 Mean score on the general mood-state question before and after the practice phase, as a function of hand contraction protocol. Error bars represent standard error of the mean. * p < .05.

None of the four questions regarding the mood-state during the motor task revealed significant differences between groups; anger, F(2,47) = 1.36, p = .267, frustration, F(2,47) = 1.51, p = .233, irritation, F(2,47) = 0.37, p = .691, and boredom, F(2,47) = 0.20, p = .823 (see Table 5.2).

Table 5.2 Mean and SD of mood-state associated with the motor task.

Group	Left-hand contractions		Right-hand contractions		No hand-contractions	
	M	SD	M	SD	M	SD
Anger	3.13	1.59	3.38	1.41	3.88	0.81
Frustration	2.88	1.03	3.25	1.13	3.56	1.21
Irritation	2.69	1.20	3.00	1.03	2.81	0.83
Boredom	2.69	1.08	2.88	1.20	2.94	1.24

5.5 Discussion

This study is the first to examine the effects of hand contractions on motor learning. Hoskens et al. (2020, Chapter 4) suggested that pre-performance left-hand contractions reduced verbal-analytical engagement in motor planning, so we predicted that left-hand contractions during practice would promote implicit motor learning by reducing explicit processes (e.g., hypothesis testing) that are usually associated with verbal-analytical engagement in performance. However, our measures suggested that there was no effect of hand contraction protocols on verbal-analytical engagement in performance. Self-reported levels of technique change and changes in kinematics (SD of velocity and angle at impact) during the practice phase were not different between the groups. Changes in SD of velocity were consistent with the power law of practice, suggesting that early in practice participants putted the ball with too much or too little force, but attuned quickly to the force (and thus velocity) that was appropriate. Changes in SD of face angle, however, improved gradually throughout practice. Additionally, recall of performance outcome after retention test 1 was not different between groups. Furthermore, no between-group differences in golf-putting performance accuracy (radial error and directional error) were evident during the practice phase, with all groups becoming more accurate gradually over blocks. During the test phase, both hand contraction groups demonstrated worse golf-putting performance than the no hand-contraction (control), suggesting that hand contractions interfered with the learning process. Additionally, dual-task putting performance was lower in all three

groups compared to single-task performance (both retention tests), suggesting that performance of the golf putting task was equally resource demanding in the groups. The kinematic measures did not change significantly during dual-task performance, however. Possibly, the measures were not sufficiently sensitive to detect change in performance.

One possible explanation for these findings is that our hand-contraction protocols did not induce hemispheric asymmetry. This assumption is supported by the results of the line bisection tasks, which showed that all groups displayed a similar bias when asked to mark the exact middle of the horizontal lines. These results are not consistent with findings of Goldstein et al. (2010), who revealed greater leftward bias for left-hand contractions. However, our hand contraction protocol differed from other protocols that have been used, raising questions about the impact of timing and duration of hand contractions on hemispheric asymmetry. Other studies have failed to demonstrate an effect of hand contractions on spatial bias (Baumann, Kuhl, & Kazén, 2005; Moeck, Thomas, & Takarangi, 2019; Propper et al., 2013; Turner et al., 2017), so the line bisection task simply may not be a suitable manipulation check in this context.

It is well established that skilled performance is characterised by cortical specificity, with resources gated towards regions that are essential for performance and inhibited in regions that are less essential for performance (e.g., Gallicchio & Ring, 2019; Hatfield & Kerick, 2007; Haufler et al., 2000); however, research has shown that this cortical specificity can be reversed under pressure conditions (e.g., Hatfield et al., 2013). Beckmann et al. (2013) demonstrated that pre-performance left-hand contractions, prior to task performance prevented choking under pressure compared to right-hand contractions for semi-professional athletes. Beckmann et al (2013) argued that left-hand contractions might have prevented choking by increasing right hemisphere (visuo-spatial) activity and reducing left hemisphere (verbal-analytic) activity,[36] thereby shifting patterns of cortical activity towards

[36] Mesagno, Beckmann, Wergin, and Gröpel (2019) have since modified this argument. On the basis of evidence that hand contractions cause cortical relaxation over the entire scalp (Cross-Villasana, Gropel, Doppelmayr, & Beckmann, 2015), they argued that reduced left hemisphere activity following left hand contractions is a function of cortical relaxation in both hemispheres. Gropel, Doppelmayr, & Beckmann, 2015), they argued that reduced left hemisphere activity following left hand contractions is a function of cortical relaxation in both hemispheres.

those associated with more automatic performance. For novices, however, optimal patterns of cortical activity may differ or may need to develop over time (Bellomo et al., 2018; Gallicchio et al., 2017). Accordingly, the use of pre-performance hand contractions may help to maintain previously established (optimal) patterns of cortical activity in experts but not deliver the same performance-benefits for novices at the initial stages of motor learning. Instead, both right-hand contractions and left-hand contractions may disrupt learning compared to no hand-contractions. Future research should adopt neurological measures (e.g., electroencephalography) to gain more insight into the cognitive processes that are influenced by the hand contraction protocols during practice. Furthermore, adding more practice trials or comparing experts with novices, might reveal whether the hand contraction protocols have a different effect on later stages of learning.

It is also possible that hand contractions may have been distracting or have caused muscle fatigue, which might have interfered with golf putting performance. Alternatively, the influence of left-hand contractions may have been superseded by the activation of the muscles of the right hand during putting, beginners may use predominantly their dominant hand to power and/or guide their movements during putting. Future research should therefore control for this possibility by utilizing tasks that do not require use of the hands (e.g., soccer penalty kicks).

Participants reported significantly lower overall mood-state following the practice phase, compared to before the practice phase. This may have been caused by boredom or possibly frustration associated with the putting task. Beginners often become frustrated when they first practice a task, simply because they do not perform at the level they expect of themselves. Between-group effects of the hand contraction protocols on mood-state specific to golf putting practice (anger, frustration, irritation and boredom) were not evident. This finding is not consistent with Propper et al. (2017) and Schiff and Lamon (1994), who revealed that hand contractions influenced mood-state. Specifically, right-hand contractions resulted in more positive mood-state, presumably as a result of activating the left hemisphere. However, the experiments by Propper et al. (2017) and Schiff and Lamon (1994) did not examine emotional states associated with motor practice, which may explain why the results of our study are not similar. Rather than focus on emotions, studies have increasingly started to examine approach and avoidance behaviour in relation

to hemisphere asymmetry (see Kelley, Hortensius, Schutter, & Harmon-Jones, 2017, for a review). This is based on evidence that hemisphere activity is more related to approach or avoidance motivation that might occur to the emotions that are felt (Harle & Sanfey, 2015; Harmon-Jones et al., 2003). Consequently, approach and avoidance should be addressed in further studies of hand contraction effects on motor learning, as this might also have an effect on cognitive processes and behaviour during motor learning (e.g., Koch, Holland, & van Knippenberg, 2008; Saarikallio, Luck, Burger, Thompson, & Toiviainen, 2013).

A final limitation is that although we used a study design similar to Zhu et al. (2015), we did not use an appropriately delayed retention test. Delayed retention tests are often conducted after at least a day, allowing effects of practice, such as boredom or fatigue, to fully dissipate, and processes associated with learning to consolidate (e.g., Shea, Lai, Black, & Park, 2000).

To conclude, we found no effect of hand contractions on self-report or objective measures of verbal-analytical engagement by novices when performing golf putting trials. Golf putting performance in the retention tests was worse for both hand contraction groups compared to the no hand-contraction (control) group, and all groups performed worse when asked to carry out a secondary task (tone counting) concurrently with golf putting. Taken together, these initial findings suggest that left-hand contractions are unlikely to promote implicit motor learning. However, given that the study did not include an explicit learning control group and that the manipulation check calls into question whether the hand contraction protocols even had the desired effect on hemisphere asymmetry, we feel that further studies are needed in order to gain a fuller understanding of the potential effect of hand contractions on implicit and explicit motor learning.

Chapter 6
General discussion

6.1 Aims and key findings

Several implicit motor learning paradigms have been developed that influence working memory involvement in motor performance either indirectly by reducing the need (or the opportunity) to engage working memory in verbal-analytical processing (e.g., Masters, 1992; Maxwell et al., 2000; Maxwell et al., 2003; Maxwell et al., 2001) or by directly suppressing cortical areas thought to be associated with verbal working memory activity (Zhu et al., 2015). The paradigms that influence working memory involvement indirectly (e.g., dual-task learning, analogy learning, error-reduced practice) (see Masters et al., 2019, for an overview) have been criticized for leaving opportunity for verbal-analytical engagement in movements, especially by people with high working memory capacity or a high propensity to engage in conscious motor processing (e.g., Buszard, Farrow, et al., 2017; Maurer & Munzert, 2013). The paradigms that influence working memory involvement directly (e.g., tDCS over the left dorsolateral prefrontal cortex, Zhu et al., 2015), might be more effective; however, they are not always easy to apply (Davis, 2013). Based on the literature that discusses these paradigms, as summarised in Chapter 1, it was argued that alternative methods of working memory suppression are needed. Therefore, the overall aim of this thesis was to test two new potential implicit motor learning paradigms, cognitive fatigue and pre-performance left-hand contraction protocols.

Experiment 1 (Chapter 2) revealed that a previously validated computer-based cognitive fatigue task (see Borragan et al., 2016) was not sufficient to suppress working memory and thus reduce verbal-analytical engagement during performance of a complex motor skill (i.e., golf-putting), compared to a non-fatigue control condition. Therefore, in Experiment 2 (Chapter 3), a new motor-related cognitive fatigue task was developed to place high demands on executive functions involved in motor tasks (i.e., inhibition, updating, switching). The task caused

cognitive fatigue, and suppressed working memory functions, but resulted in more, rather than less, verbal-analytical engagement (e.g., hypothesis testing) during practice of a shuffleboard task, compared to a non-fatigue control condition.

Experiment 3 (Chapter 4) showed that left-hand contractions reduced cortical activity in the left hemisphere and lowered verbal-analytical engagement in motor planning during a golf putting task; whereas, right-hand contractions increased cortical activity in the left hemisphere and raised verbal-analytical engagement in motor planning. Experiment 4 (Chapter 5) therefore examined whether left-hand contractions promote implicit motor learning. The results revealed, however, that left-hand contractions prior to practicing a golf-putting task did not reduce verbal-analytical processing of movements and thus did not cause implicit motor learning.

6.2 The effects of cognitive fatigue on verbal-analytical processes associated with motor performance

Zhu et al. (2015) used tDCS prior to motor performance (a golf putting task) to suppress neural activity over the left dorsolateral prefrontal cortex, an area associated with verbal working memory processes. Zhu et al. (2015) concluded that this strategy had potential to cause implicit motor learning. Based on the findings of Zhu et al. (2015), Experiments 1 and 2 of this thesis investigated whether cognitive fatigue tasks can be used as a non-invasive method to suppress working memory. The computer-based cognitive task in Experiment 1 did not cause an effect on cognitive processes during motor performance. Therefore, the fatigue treatment developed in Experiment 2 targeted working memory related to motor control. Contrary to the predictions, verbal-analytical engagement in motor planning increased rather than decreased. An explanation for the different findings in the two experiments can be found in dual-regulation approaches to mental fatigue (Ishii et al., 2014). Ishii et al. (2014) proposed that workload associated with cognitive tasks can activate two different systems; a mental facilitation system that maintains cognitive performance in the presence of fatigue and a mental inhibition system that decreases cognitive performance in order to maintain homeostasis. The inhibition system can easily be activated during low demand tasks because they often evoke minimal motivation or are boring, whereas, the facilitation system can be easily

activated during demanding tasks because they are more likely to evoke motivation or are interesting/challenging. The high demand task that we tested in Experiment 2 may therefore have raised the interest or motivation of participants more than the low demand task that we tested in Experiment 1. The workload associated with the high demand task would therefore have activated the facilitation system, which may have manifested in elevated engagement in verbal-analytical processing to compensate for the effects of fatigue. Poolton et al. (2007) used a similar line of reasoning to explain the role of verbal-analytical engagement in motor performance under physiological fatigue. They examined performance of a rugby passing task under fatigue (a double Wingate task) following error-reduced and error-strewn practice. Error-reduced practice is designed to reduce verbal-analytical engagement in performance by minimising the number of errors made during practice, whereas error-strewn practice is designed to raise verbal-analytical engagement in performance by increasing the number of errors made during practice.

Poolton et al. (2007) found that performance after error-reduced practice remained stable when participants were severely fatigued, but performance following error-strewn practice was disrupted. They argued that performance by participants in the error-strewn group may have been disrupted because they resorted to verbal-analytical processing of their performance, which was inappropriate for maintaining performance in the presence of fatigue. In Experiment 2 of this thesis, it is possible that participants also resorted to verbal-analytical processes to consciously control movement execution, in order to compensate for the negative effects of fatigue. The theory of reinvestment, however, argues that consciously controlling movement execution can disrupt normally efficient motor behaviours, often causing worse motor performance (Masters, 1992; see Masters & Maxwell, 2008, for a review).

Poolton et al. (2007) also proposed an alternative explanation for their results, arguing that fatigue may have distracted working memory from its primary functions, allowing attention to be directed towards task-irrelevant information (e.g., perceived feelings of fatigue and discomfort). Consequently, working memory was less available for verbal-analytical engagement in motor skill performance, causing decreased motor performance by participants in the error-strewn group (because they relied on verbal processes). Participants in the error-reduced group, however,

did not rely on verbal processes (and thus did not need working memory), so their motor performance remained stable. This argument is consistent with Attentional Control Theory (ACT, Eysenck, Derakshan, Santos, & Calvo, 2007), which proposes that anxiety (possibly also cognitive and/or physical fatigue) reduces the ability to inhibit processing of task-irrelevant information (i.e., worrisome thoughts), which occupies working memory resources.

ACT assumes that there are two attention control systems: a goal-directed (top-down) system and a stimulus-driven (bottom-up) system (Corbetta & Shulman, 2002). The goal-directed system is influenced by current goals and expectations, whereas the stimulus-driven attention system responds to task salient stimuli. When anxiety levels increase, the goal-directed system can be overpowered by the stimulus-driven system, causing attention to be directed to salient stimuli that may be irrelevant, which can cause decreased performance (Allsop, Lawrence, Gray, & Khan, 2017; Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008; Wilson, Vine, & Wood, 2009; Wilson, Wood, & Vine, 2009). For instance, anxiety when taking a penalty shot under pressure may cause a soccer player to direct attention to stimulus-driven information, such as the goalkeeper's movements. However, focussing on the goalkeeper's movements, rather than target-specific locations (e.g., corners of the goal) may cause shots to be directed closer to the goalkeeper (e.g., Bakker, Oudejans, Binsch, & van der Kamp, 2006; van der Kamp & Masters, 2008; Wilson, Wood, et al., 2009; Wood & Wilson, 2010). Eysenck et al. (2007), however, also showed that in some cases these negative effects of anxiety can be offset by utilizing additional cognitive resources or investing more effort. In Experiment 2 of this thesis, cognitive fatigue did lead to higher verbal-analytical engagement in motor planning, but did not cause decreased performance. Based on this, it could be a possibility that participants in Experiment 2 invested more effort and wrestled back top-down control of performance (Nieuwenhuys & Oudejans, 2012).

Another explanation for the increased verbal-analytical engagement in motor performance, might be that cognitive fatigue reduces the efficiency of working memory, which actually increases use of verbal-analytical resources. This prediction might be explained by the model in Figure 6.1, which is based on Masters and Maxwell (2004). The model suggests that implicit motor control can be initiated directly by perception (stimuli), which does not make use of working memory

processes. Explicit motor control, however, utilizes working memory processes to manipulate verbal information associated with movement outcome feedback. During explicit learning, working memory functions become more and more efficient at picking up relevant stimuli from the environment and at inhibiting irrelevant stimuli. This is supported by previous studies revealing that experts have better executive functions (see Scharfen & Memmert, 2019, for a review), which might reflect the development of efficient working memory functions during motor practice. Accordingly, as long as working memory can efficiently pick up relevant information and inhibit irrelevant information, explicit motor control can occur relatively successfully. Consistent with the findings presented by Vogel et al. (2005), efficient working memory may be associated with processing and temporary storage of less, but task-relevant, information (i.e., stimuli). However, when, for example, pressure or fatigue interferes with working memory efficiency, processing and temporary storage of both task-relevant and -irrelevant stimuli might occur, which increases hypothesis testing because more possible motor solutions (irrelevant and relevant) are available. This potentially results in increased accretion of explicit (declarative) knowledge. Based on this rationale, it may be the case that in Experiment 2 working memory efficiency was disrupted by fatigue, which caused both relevant and irrelevant stimuli to be picked up or processed, causing greater hypothesis testing (i.e., greater verbal-analytical engagement).

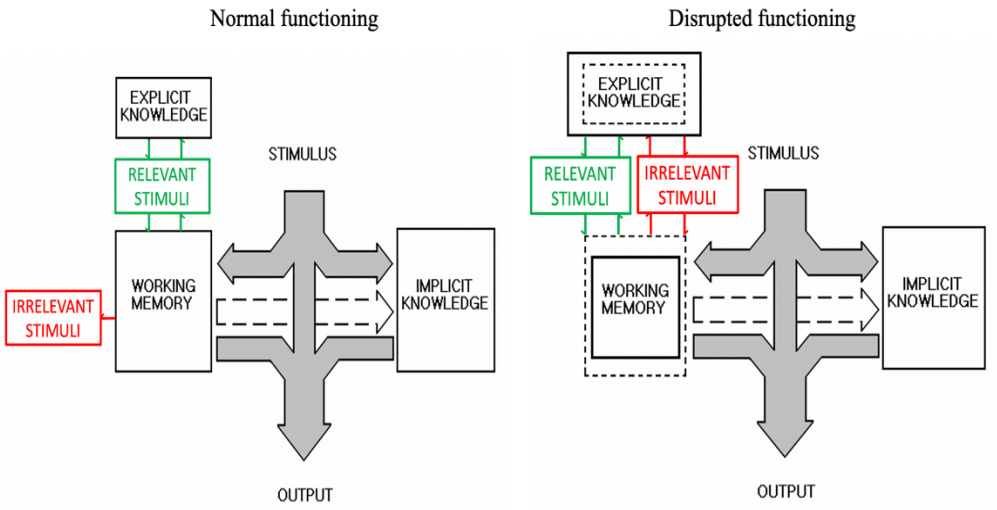

Figure 6.1 A model based on Masters and Maxwell (2004), outlining the role of working memory in implicit and explicit motor learning. The left panel shows what might occur when normal functioning occurs. The right panel describes the outcome when disrupted functioning of working memory functions occurs, creating an increased flow of stimuli that contribute to explicit knowledge.

One final consideration is that cognitively demanding tasks enhance, rather than suppress, cognitive processes. Kimura and Nakano (2019) revealed that an N-back task performed for 20 min prior to motor learning, improved performance in the early learning stages of a simple motor skill[37] compared to participants who did not perform the N-back task. Kimura and Nakano (2019) therefore predicted that the N-back task activated cognitive processes, benefitting the early cognitive stages of motor learning. However, they did not use neurological measures (e.g., EEG), and therefore they could not make firm conclusions about what kind of cognitive processes were enhanced by the N-back task. Nevertheless, based on Kimura and Nakano (2019) it can be suggested that the cognitive task utilized in Experiment 2 enhanced activation of cognitive processes, which might have primed increased cognitive processes, such as a verbal-analytical engagement during (early) motor performance.

[37] The motor task consisted of a mouse tracking task, which required participants to learn how to adjust he movement of the mouse to move a cursor on a computer screen towards the target.

Regardless, the results of Experiments 1 and 2 suggest that cognitive fatigue did not suppress executive functions (i.e., inhibition, updating, switching) to such an extent that verbal-analytical processing of movements was reduced equally to tDCS over the left dorsolateral prefrontal cortex (Zhu et al., 2015).

6.3 Hand contractions and verbal-analytical processes

Voluntary movements involve two phases of motor control. The first phase involves processing and correcting movement errors (often between movements), whereas, the second phase involves preparing and controlling movements (just prior to initiation of movement until the movement ends) (e.g., Allsop et al., 2017; Glover, 2004). Based on the findings from Experiments 3 and 4, it could be argued that the hand contraction protocols mostly influenced motor control in the second phase, just prior to movement initiation, rather than in the first phase, between movements. Specifically, in Experiment 3, left-hand contractions reduced verbal-analytical engagement just prior to movement initiation. However, in Experiment 4, left-hand contractions did not promote implicit motor learning, suggesting that participants may have engaged in processing and correcting their movement errors (i.e., hypothesis testing). This implies that left-hand contractions could suppress verbal-analytical processing during movement preparation and control, but have no impact on the processing and correction of errors in between trials. Consequently, hypothesis testing would have occurred between trials and resulted in accretion of explicit knowledge. Furthermore, automatization of a motor skill is not only associated with inhibited activity in the left temporal region, but also with inhibited activity in the occipital regions (Gallicchio & Ring, 2019). The occipital region is involved in visual processes (e.g., Beckers & Hömberg, 1991), which might include picking up information about movement outcome (e.g., knowledge of results) that is necessary for error processing and correction. Perhaps, therefore, inhibition of both left-temporal and occipital processing is required to suppress both verbal-analytic engagement and hypothesis testing. Left-hand contractions may suppress activity in the left temporal region only. To overcome this issue, visual occlusion of feedback could be used in conjunction with left-hand contractions. Visual occlusion can be used to reduce occipital activation by preventing visual processing of knowledge of results following practice trials. Masters, Maxwell, and Eves (2009) showed that this reduced explicit processing (i.e., error processing and correction)

of outcome information between trials, by removing the ability (and or motivation) to test hypotheses about performance. Masters et al (2009) tentatively concluded that visual occlusion of feedback might promote implicit motor learning. However, the findings from this thesis suggest that a more effective approach might be to combine visual occlusion with left-hand contractions - visual occlusion of feedback could be used to reduce explicit motor planning between trials, and left-hand contractions could be used to suppress working memory interference in preparing and controlling movements just prior to movement initiation. Future studies are warranted to test this hypothesis.

The above explanation for why implicit motor learning was not promoted by left-hand contractions does not explain why both left-hand and right-hand contractions in Experiment 4 caused worse performance during the test phase (i.e., retention and transfer tests after practice), compared to no hand-contractions. It is, however, known that skilled performance is characterised by cortical specificity, in which brain regions essential for task performance are activated and brain regions that are not essential are inhibited (e.g., Gallicchio & Ring, 2019; Hatfield & Kerick, 2007; Haufler et al., 2000). For novices, however, cortical specificity may be different or may need to develop with practice (Bellomo et al., 2018; Gallicchio et al., 2017). Therefore, hand contractions might not deliver the same performance benefits for novices in the early stages of motor learning as they might later in learning, when their motor skills are more established. Instead, both left-hand and right-hand contractions may have disrupted learning compared to no hand-contractions. In line with this, previous studies have revealed that early stages of learning may actually benefit from verbal-analytical processing and conscious control of movements, whereas later stages may be disrupted (e.g., Beilock, Wierenga, & Carr, 2002; Gray, 2004; Jackson et al., 2006; Malhotra et al., 2015). Accordingly, pre-performance hand contractions that influence verbal-analytical engagement in performance may be useful when more optimal patterns of cortical activity have begun to emerge later in learning, or when experts perform under pressure (as shown by Beckmann et al., 2013; Gröpel & Beckmann, 2017).

6.4 Neural processes involved in implicit motor learning

Historically, researchers interested in cortical indices of verbal-analytical engagement in movement have mainly been interested in activity in the left temporal areas of the brain (e.g., Kerick et al., 2001; Landers et al., 1991; van Duijn et al., 2019). Recently, however, it has been suggested that rather than focusing on specific scalp locations (e.g., left temporal) at a single point in time, researchers should monitor the activity of the whole scalp to reveal how activation is gated and how different areas interact with one another as verbal-analytical processes and conscious control varies across time, or between different experimental conditions (e.g., Bellomo, Cooke, Gallicchio, Ring, & Hardy, 2020; Gallicchio & Ring, 2019; Parr, Gallicchio, Harrison, Johnen, & Wood, 2019). For example, Gallicchio and Ring (2019) used the gating-by-inhibition model (Jensen & Mazaheri, 2010) to examine how alpha activity channels cognitive resources to appropriate regions of the brain during random practice (position of target changed within block) or blocked practice (position of target only changed between blocks) of a golf putting task. Movement-related alpha gating is a mechanism that has been proposed to underpin development of psychomotor efficiency (Hatfield & Hillman, 2001), where appropriate motor areas are activated and inappropriate nonmotor areas are deactivated during motor performance. Movement-related alpha gating causes any neural activation in regions of the brain deemed to be less important for the task to be inhibited (indexed by alpha power increases) and instead channelled to regions deemed more important (where alpha power decreases). Gallicchio and Ring (2019) revealed that practice caused cognitive activity during movement preparation in both the random practice and the blocked practice group to be diverted away from processing in the occipital, temporal and frontal regions, towards processing in the central regions of the brain. They concluded that the left temporal and occipital regions are involved in the early (cognitive) stages of motor learning, and must be inhibited to improve performance (i.e., become expert). Inhibition of the occipital and temporal regions was associated with better performance, which caused them to speculate that processes supported by these regions of the brain (e.g., retrieval of declarative knowledge) can disrupt performance if not restrained. These claims are consistent with the philosophy underlying implicit motor learning and the theory of reinvestment (Masters, 1992). Future research should examine whether the implicit

motor learning paradigms that have been designed to prevent accretion (and/or retrieval) of task-relevant declarative knowledge (e.g., error-reduced practice, analogy learning etc), promote greater or more rapid movement-related alpha gating, compared to explicit motor learning.

In addition to focusing on left-temporal activation, previous research has also advocated T7-Fz connectivity as a neural index of conscious motor processing (e.g., Zhu, Poolton, Wilson, Maxwell, et al., 2011). The wealth of previous research in this area (see Cooke, 2013, for a review) informed the use of T7-Fz connectivity as a dependent measure in this thesis. However, very recently, some researchers have begun to question the robustness of this measure. For instance, it should be noted that connectivity is merely a measure of the phase lag consistency between signals at (only) two sites, meaning pathways of communication are implied rather than directly measured (Bellomo et al., 2020; Bellomo et al., 2018; Cohen, 2014; Parr et al., 2019). This raises doubts about claims that reduced T7-Fz connectivity can be adopted as a direct measure of implicit motor performance in all situations. For example, Bellomo et al. (2020) measured T7-Fz connectivity and connectivity between frontal Fz and other sites (occipital, parietal and central) while novices practiced golf putts reciting either instructional (e.g., "feet still, wrists locked, arms through") or motivational self-talk ("come on, I can do this"). Contrary to their hypothesis, Bellomo et al. (2020) found less connectivity between Fz and other sites during instructional compared to motivational self-talk. It was suggested that the amount of connectivity with Fz reflects the degree to which sensory processes (e.g., visual and perceptual) influence motor planning. Following this reasoning, it was suggested that explicit movement instructions could reduce the influence of sensory processes in some circumstances by promoting top-down control. This evidence urges caution in the interpretation of T7-Fz connectivity as a neural index of conscious motor processing. However, in defence of the T7-Fz measure, one could argue that self-talk, as employed by Bellomo and colleagues, may not be representative of the type of verbal-analytical processing (or internal movement dialogue) that occurs during explicit and implicit motor learning/performance. For one thing, an experimental instruction to self-talk (regardless of the topic of the self-talk) requires a person to try to become aware explicitly of their thoughts (i.e.,

introspect), which as James (1890/1950) famously claimed, is as pointless as trying to seize “a spinning top to catch its motion” (p. 244).

Cognitive fatigue and hand contractions were associated with differences in T7-Fz connectivity in this thesis. In particular, the cognitive fatigue method utilized in Experiment 2 revealed T7-Fz results that were consistent with the behavioural measures of verbal-analytical engagement in motor performance (i.e., more technique changes were associated with higher T7-Fz connectivity). Therefore, T7-Fz might well be an informative gauge of verbal-analytical processing during motor performance, but it is important to not only rely on this measure.

Other frequency bands besides the alpha range, might also play a role in verbal-analytical processing of movement. Some research suggests that theta power over the frontal regions is an indicator of mental effort, concentration, and also working memory processes during motor preparation (Baumeister, Reinecke, Liesen, et al., 2008; Chuang, Huang, & Hung, 2013; Cooke, 2013; Doppelmayr, Finkenzeller, & Sauseng, 2008; Hatfield & Kerick, 2007; Haufler et al., 2000; Kao, Huang, & Hung, 2013; Kerick & Allender, 2006). However, these studies have demonstrated mixed results and used different EEG designs to study frontal theta power. For instance, Baumeister, Reinecke, Liesen, et al. (2008) did not use event-locked EEG (i.e., measuring the EEG signal in relation to a specific event like motor planning), but instead recorded EEG activity continuously over 4 min, which does not specifically provide information about motor planning. Furthermore, Doppelmayr et al. (2008) revealed that higher frontal theta power was associated with better attention focus, whereas Kao et al. (2013) revealed that lower frontal theta power was associated with better attention focus. Theta power is not reported in this thesis, but future studies should do so in order to gain broader insight into the mental processes associated with motor learning and performance.

Last but not least, the cerebellum has been implicated in working memory processes (i.e., the phonological loop) (Bellebaum & Daum, 2007), and also in implicit learning (e.g., Koziol, Budding, & Chidekel, 2012; Taylor, Klemfuss, & Ivry, 2010). Specifically, the cerebellum is thought to store sensory and output information generated by the prefrontal regions during motor processing. The cerebellum then adjusts this output according to errors made and provides the prefrontal cortex with the most efficient procedural motor processes, which is

revealed to be important for implicit adaptation of movements (e.g., Ferrucci et al., 2013; Ito, 2005; Koziol et al., 2012; Lang & Bastian, 2002; Taylor et al., 2010). It has been generally accepted that information processes occurring in the cerebellum occur outside conscious awareness (Ito, 2005). Lang and Bastian (2002), for instance, showed that patients with cerebellar degeneration [38] were unable to automatize a motor skill. The patients and age-matched control participants practiced a motor task (i.e., upright standing while performing a number eight movement with the arm). After practice, a dual-task was performed in which participants performed the same motor task concurrently with an auditory vigilance task (i.e., indicating the number of times a target letter occurred in a sequence of letters). The control participants were not influenced by the dual-task condition, but, the patients showed decreased performance. Therefore, Lang and Bastian (2002) concluded that the cerebellum was necessary for shifting motor task performance to an automatic state. Furthermore, Ferrucci et al. (2013) revealed that anodal tDCS (activation) over the cerebellum improved implicit learning of a sequence reaction time task. A speculation that emerges from these claims is that the cognitive fatigue task in Experiment 2 disrupted cerebella activity (as well), which suppressed development of movement automatization. A consequence of this could be increased verbal-analytical engagement during motor performance.

In summary, cognitive processes occur flexibly in response to environmental and task demands, and it is unlikely that a single region of the brain is linked to specific cognitive processes underlying motor performance. Future studies should therefore utilize broader measures of cognitive processing and interpret neurological measures in tandem with behavioural measures. This will give better insight into why cognitive fatigue causes increased hypothesis testing in motor performance and why left-hand contraction protocols do not cause beneficial (implicit) motor learning for novices. Further predictions may then emerge for how to reduce cognitive processes that promote explicit motor learning and increase those involved in implicit motor learning.

[38] A condition in which neurons become damaged and progressively weaken in the cerebellum.

6.5 Practical applications

The findings presented in this thesis suggest that completion of a cognitively fatiguing motor task before practice does not promote implicit motor learning by reducing verbal-analytical engagement in motor control. In the context of skills training, our findings suggest that a cognitively demanding drill (e.g., highly strategic) that fatigues a performer mentally may, in fact, increase verbal-analytical engagement. Cognitive fatigue may therefore be useful in cases where increased verbal-analytical engagement is strategically useful, such as when novices are first learning a skill (Malhotra et al., 2015) or when experts are perfecting their technique (Toner & Moran, 2015) or attempting to alter long engrained movement patterns (Sperl & Cañal-Bruland, 2019). However, physical performance, and technique, often deteriorate when athletes are cognitively fatigued (e.g., Smith, Coutts, et al., 2016; Smith, Fransen, Deprez, Lenoir, & Coutts, 2016), so care needs to be taken.

Cognitive fatigue may also be useful when applied in different strategic motor control scenarios, such as in Esports, where increased verbal-analytical engagement is potentially beneficial for complex tactical decision-making (e.g., which weapon is best purposed for this form of combat) (Martin-Niedecken & Schättin, 2020). However, cognitive fatigue has also been linked to poor decision making by athletes (e.g., Coutinho et al., 2017; Smith, Zeuwts, et al., 2016). For example, Coutinho et al. (2017) revealed that tactical performance by players was reduced in a small-sided football game after they had performed a cognitive motor task (i.e., different coordination movements on a speed ladder). Consequently, further research is needed to establish whether cognitively fatiguing motor tasks are useful or not in these different situations.

Pre-performance left-hand contraction protocols might be an easier, more efficient, method to apply in practical sports settings, because simply squeezing a ball for approximately 45 sec before performing a motor skill is relatively simple to do. Pre-performance left-hand contractions have already been shown to cause better performance by semi-professional athletes under pressure (Beckmann et al., 2013; Gröpel & Beckmann, 2017). Beckmann and colleagues claimed that pre-performance left-hand contractions reduced susceptibility to movement failure under pressure by suppressing verbal-analytical engagement in motor planning. The

findings in this thesis not only provide some support for the Beckmann et al findings, but also suggest that left-hand contractions may be more effective for those who have a high propensity for conscious motor processing, as it is likely that they perform a movement with higher levels of verbal-analytical engagement (i.e., movement specific reinvestment) (Masters & Maxwell, 2008).

This thesis mainly focused on young adults; however, the results could potentially also be applied to older adults and patients with cognitive impairments. Older adults and patients with cognitive impairments generally have not only reduced cognitive abilities compared to young adults (Owen, Iddon, Hodges, Summers, & Robbins, 1997; Pendlebury, Cuthbertson, Welch, Mehta, & Rothwell, 2010; Verbaan et al., 2007), but also disturbed motor control, which can make them highly verbal about their movement execution (e.g., Denneman, Kal, Houdijk, & Kamp, 2018; Orrell et al., 2006b). Conscious motor processing is associated with motor problems during skilled performance and every-day activities by older adults (e.g., Chauvel et al., 2012), Parkinson's disease patients (e.g., Masters et al., 2004), stroke patients (e.g., Orrell et al., 2009) and patients with Cerebral Palsy (van Abswoude et al., 2015). Consequently, it has been argued that it is more beneficial for these populations to perform movements with less verbal-analytical engagement (i.e., more implicitly) (e.g., Chauvel et al., 2012; Masters et al., 2004; Orrell et al., 2006b). For example, Masters et al. (2004) revealed that Parkinson's patients learning a hammering task in an error-reduced condition performed better under a secondary task load (i.e., counting backwards) compared to Parkinson's patients learning the hammering task in an error-strewn condition. Furthermore, physiotherapists often use highly explicit motor performance instructions, which promote verbal-analytical processing by patients. For example, Johnson, Burridge, and Demain (2013) revealed that physiotherapists gave one verbal instruction (or item of verbal feedback) every 14 sec during rehabilitation sessions with stroke patients. It is therefore important to look for alternative implicit motor learning methods that can be easily applied by therapists (Kleynen, Beurskens, Olijve, Kamphuis, & Braun, 2020).

Performing a cognitively demanding motor task before motor practice is unlikely to be favourable for older adults and patients with reduced cognitive resources, as Experiment 2 revealed that cognitive fatigue increased verbal-

analytical engagement. Hence, cognitive fatigue should be avoided by these groups. For instance, introducing a cognitively challenging therapy prior to or during a physiotherapy session could lead to increased verbal-analytical engagement in movements and, potentially, reduced motor efficiency. Alternatively, it could promote explicit relearning when implicit relearning is preferred. Consequently, therapists need to be careful about the amount of cognitive demand they create during physiotherapy sessions or to structure rehabilitation sessions in ways that limit accumulation of cognitive fatigue.

Left-hand contraction protocols might be a more favourable protocol to apply in physiotherapy sessions or during rehabilitation for patients and older adults, if the aim is to reduce verbal-analytical engagement in motor planning. Specifically, given that these populations are shown to be highly explicit about their movements, it might be beneficial to perform left-hand contractions before motor (re)learning. Alternatively, hand contraction protocols may be useful as a supplementary form of implicit motor learning, alongside more established approaches, such as analogy learning. Jie et al. (2016), for instance, used analogies to improve stride length regulation by Parkinson's patients. Hand contractions could easily be utilised alongside analogies during tasks such as walking. Should they be experienced as too difficult, painful or exhausting, simplified methods of hand or finger movements might potentially also influence verbal-analytical engagement. Further research is needed.

6.6 Summary and future studies

In summary, the results of this thesis suggest that cognitive fatigue before motor practice caused working memory suppression, which led to increased rather than decreased verbal-analytical processing of movement execution. Left-hand contractions, however, provided a more promising method of suppressing working memory in order to reduce verbal-analytical processing, as shown by our EEG data. However, left-hand contractions prior to practicing a complex movement skill (i.e., golf putting) did not appear to promote implicit motor learning.

The left-hand contraction protocols might still have potential to benefit motor learning, as Experiment 3 of this thesis revealed that left-hand contractions reduced verbal-analytical engagement in motor planning. Therefore, further

research is needed to examine neural aspects of the interaction between motor learning and hand contraction protocols. Furthermore, long-term practice studies with delayed retention tests are needed to examine the effects of hand contraction protocols on motor learning. It would also be of interest to examine whether the effects of hand contraction protocols is different for experts versus novices - it might simply be that left-hand contraction protocols have more beneficial effects for experts than novices, but we are unable to comment given that we only examined novices. Additionally, there are numerous confounding factors in hand squeezing literature, which need to be controlled. For example, the force (or duration of force) with which an object is squeezed might influence the effects (or duration of effects) on cortical activity, but this has not been examined.

Another aspect, which should be examined in regards to motor skill learning and hand contraction protocols is approach and avoidance motivation. Previous research has shown that motivation enhances learning; however, there are different ways to motivate people to learn (e.g., Kazdin, 2012; Murty, LaBar, Hamilton, & Adcock, 2011). In approach motivation, behaviour is directed by a possibility for a desired outcome, whereas in avoidance motivation, behaviour is directed by a possibility for an undesired outcome (Elliot, 1999; Elliot & Covington, 2001). It has been shown that approach motivation is associated with cortical activity in the left hemisphere, whereas avoidance motivation is associated with cortical activity in the right hemisphere (e.g., Harmon-Jones, 2003). Because approach and avoidance motivation are associated with different hemispheres, extensive research has been conducted to examine how hand contraction protocols influence these motivation types. Specifically, most studies have revealed that left-hand contractions cause more avoidance motivation, whereas right-hand contractions cause more approach motivation (Harle & Sanfey, 2015; Harmon-Jones, 2006; Peterson, Gravens, & Harmon-Jones, 2011). Approach motivation may promote trial-and-error type of learning (i.e., reflective of verbal-analytical engagement) because it encourages more active search for movement solutions, whereas avoidance motivation may promote behavioural inhibition and, thus, a less solution-oriented approach (Murty et al., 2011). Future research should consider these links to approach and avoidance motivation as alternative mechanisms to those related to

verbal-analytical processes to explain any effects of unilateral hand contractions on behaviour.

Besides cognitive fatigue and left-hand contraction protocols, other methods of working memory suppression should also be considered as potential methods by which to promote implicit motor learning. For example, it may be useful to practice during an individual's *non-optimal* time of the day. Specifically, individuals have different circadian rhythm, which reflect their sleep-awake schedule (e.g., Schmidt, Collette, Cajochen, & Peigneux, 2007). Previous studies have revealed that participants learn more implicitly during the non-optimal time of the day, compared to the optimal time of the day (Delpouve, Schmitz, & Peigneux, 2014; May, Hasher, & Foong, 2005). It has been argued that this occurs because executive functions operate less efficiently during off-peak periods. Consequently, verbal-analytical engagement may be lower (i.e., less hypothesis testing) if practice occurs at non-optimal times of the day compared to optimal times of the day.

Illusory fatigue is another method that might be useful for promoting implicit motor learning. Clarkson, Hirt, Austin Chapman, and Jia (2010), for example, revealed that illusory fatigue reduced working memory performance. They suggested that it is possible to manipulate how many resources participants think they have available (i.e., when they believe that they are fatigued), regardless of how many resources are actually available. Furthermore, Minda and Rabi (2015) revealed that reducing an individual's executive functions with a resource depletion task (i.e., writing a story with an instruction to omit specific letters) resulted in reduced rule defined learning, whereas non-rule defined learning was unaffected. Consequently, illusory fatigue may reduce verbal-analytical engagement in motor performance by causing learners to avoid utilising working memory processes that are perceived as too demanding.

Two similar approaches that may also promote implicit motor learning involve taking alcohol and cannabis, both of which have been revealed to suppress working memory functions (Cohen & Weinstein, 2018), and to interfere with motor programming related executive functions (Domingues, Mendonca, Laranjeira, & Nakamura-Palacios, 2009). It could be that a small amount of alcohol or cannabis is sufficient to suppress executive functions during motor performance, thereby

reducing verbal-analytical engagement. However, this method has obvious complications with respect to health, legality and practicality.

Hypoxia, during which the body is deprived of adequate oxygen, is another method to suppress working memory. Previous studies have revealed that hypoxia reduces working memory and/or cognitive functions (McMorris et al., 2017; Yan et al., 2011), because the human body diverts resources to the cardiorespiratory system in order to maintain functions crucial for survival. It may be that implicit motor learning is promoted in an oxygen reduced environment (e.g., altitude or an altitude chamber), because disrupting working memory and/or cognitive functions in this way reduces verbal-analytical engagement in performance. Speculatively, examining whether individuals (or teams) based at higher altitudes (e.g., cities in Peru) display more characteristics representative of implicit skills (perhaps their performance is more robust under psychological or physiological pressure, for example). Performance at altitude (i.e., under hypoxia) has been examined mostly for physiological reasons (see McLean, Gore, & Kemp, 2014, for a review). Morrison, Quinn, MacDonald, Billaut, and Minahan (2019) did show that repeated treadmill training under hypoxia reduced cognitive performance of athletes, but to our knowledge motor learning during hypoxia has not been examined.

Finally, neurofeedback might offer another promising method to promote implicit motor learning, because this is a non-invasive method of targeting specific regions of the brain. Neurofeedback is a technique that allows a person learns to adjust their own brain activity by responding to visual or auditory feedback that represents on-line activity in a particular brain region and frequency band (see Cooke et al., 2018; Mirifar, Beckmann, & Ehrlenspiel, 2017, for reviews). The technique has already been honed in the context of motor performance. For example, Ring et al. (2015) revealed that recreational golfers learned to reliably increase activation over the motor cortex in the final moments preceding putts following just 3-hours of EEG-neurofeedback training. They were therefore able to mimic the pre-movement brain activation patterns of highly skilled experts. In regards, to implicit motor learning, it would be of interest to apply this technique to reduce cortical activity above left-temporal and/or occipital brain regions during the final moments of motor preparation (e.g., Gallicchio & Ring, 2019). Doing so would be expected to help inhibit non-essential verbal-analytic and visual processes from interfering

with motor programming, thereby strengthening the alpha gate and encouraging proceduralized motor control (e.g., Gallicchio & Ring, 2019; Kerick et al., 2001; Landers et al., 1991; van Duijn et al., 2019). This exciting possibility is ripe for examination by future research.

6.7 Conclusion

The brain is a fascinating and highly-complex system, and its involvement in motor performance is still not fully understood. Thus, it is important to gain better understanding of how working memory processes are involved in verbal-analytical processes associated with motor learning and performance. This thesis has contributed to such an undertaking, by examining how working memory can be suppressed in order to promote implicit motor learning. Exciting possibilities have emerged from the experiments that are presented in the thesis, enhancing, rather than suppressing, the need for hypothesis testing.

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Appendix 1: Adapted version of the Visual Analogue Scale of Fatigue (VASf, Lee et al., 1990)

Visual Analogue Scale for Fatigue (VAS-F):

Participant Number: _____ Date: _____ **(PRE)**

DIRECTIONS: You are asked to circle a number on each of the following lines to indicate how you are feeling RIGHT NOW.

For example, suppose you have not eaten since yesterday. What number would you circle below?

Not at all hungry 0 1 2 3 4 5 6 7 8 9 10 Extremely hungry

You would probably circle a number closer to the "extremely hungry" end of the line. This is where I put it:

Not at all hungry 0 1 2 3 4 5 6 7 (8) 9 10 Extremely hungry

NOW PLEASE COMPLETE THE FOLLOWING ITEMS:

1) not at all **tired**	0	1	2	3	4	5	6	7	8	9	10	extremely **tired**
2) not at all **fatigued**	0	1	2	3	4	5	6	7	8	9	10	extremely **fatigued**
3) not at all **efficient**	0	1	2	3	4	5	6	7	8	9	10	extremely **efficient**
4) **concentrating** is no effort at all	0	1	2	3	4	5	6	7	8	9	10	**concentrating** is tremendous chore

Appendix 2: Co-authorship forms

THE UNIVERSITY OF WAIKATO
Te Whare Wānanga o Waikato

Co-Authorship Form

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[redacted]

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Thesis chapter:

The effects of cognitive fatigue on conscious engagement in movement

Nature of contribution by PhD candidate	Investigator, conception, design, data collection, analysis, interpretation, drafting, revisions
Extent of contribution by PhD candidate (%)	>60%

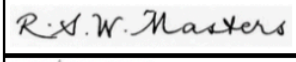
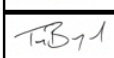
CO-AUTHORS

Name	Nature of Contribution
Ko-Tahi-Ra Boaz-Curry	Investigator, design, data collection
Liis Uiga	Comments
Tim Buszard	Conception
Catherine Capio	Comments
Andrew Cooke	Comments
Rich Masters	Significant at all stages; primary supervisor

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Prof Rich Masters		25th March 2020
Dr Liis Uiga		26th March 2020
Dr Andrew Cooke		26th March 2020
Dr. Catherine Capio		27th March 2020
Ko-Tahi-Ra Boaz-Curry		27th March 2020
Dr Tim Buszard		30th March 2020

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Thesis chapter:
The effects of fatigued working memory functions on hypothesis testing during acquisition of a motor skill

Nature of contribution by PhD candidate	Main investigator, conception, design, data collection, analysis, interpretation, drafting, revisions
Extent of contribution by PhD candidate (%)	75%

CO-AUTHORS

Name	Nature of Contribution
Liis Uiga	Comments
Andrew Cooke	Conception, design, comments
Catherine Capio	Comments
Rich Masters	Significant at all stages; primary supervisor

Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate's contribution to this work, and the nature of the contribution of each of the co-authors; and

Name	Signature	Date
Prof Rich Masters	R.A.W. Masters	25th March 2020
Dr Liis Uiga		26th March 2020
Dr Andrew Cooke		26th March 2020
Dr. Catherine Capio		27th March 2020

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Thesis chapter:

The effects of unilateral hand contractions on conscious control in early motor learning

Nature of contribution by PhD candidate	Investigator, conception, design, data collection, analysis, interpretation, drafting, revisions
Extent of contribution by PhD candidate (%)	>60%

CO-AUTHORS

Name	Nature of Contribution
Liis Uiga	Investigator, conception, design, data collection, interpretation, drafting; co-supervision
Andrew Cooke	Comments; co-supervision
Catherine Capio	Comments
Rich Masters	Significant at all stages; primary supervisor

Certification by Co-Authors

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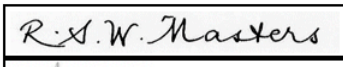
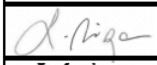
Prof Rich Masters		25 March 2020
Dr Liis Uiga		26th March 2020
Dr Andrew Cooke		26th March 2020
Dr Catherine Capio		27th March 2020

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Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work. Thesis chapter: The effect of unilateral hand contractions on psychophysiological activity during motor performance: Evidence of verbal-analytical engagement

Nature of contribution by PhD candidate	Main investigator, conception, design, data collection, analysis, interpretation, drafting, revisions
Extent of contribution by PhD candidate (%)	>60%

CO-AUTHORS

Name	Nature of Contribution
Eduardo Bellomo	Data collection, analysis
Liis Uiga	Interpreting, comments
Andrew Cooke	Supervision all stages
Rich Masters	Significant at all stages; primary supervisor

Certification by Co-Authors

The undersigned hereby certify that:

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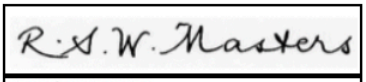
Prof Rich Masters		25th March 2020
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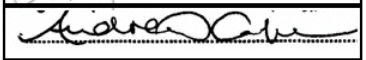
Dr Andrew Cooke		26th March 2020
Dr Eduardo Bellomo		28th March 2020